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SUPPORT COSTS AND RELIABILITY IN WEAPONS ACQUISITION: APPROACHES FOR EVALUATING NEW SYSTEMS

Karen W. Tyson, *Project Leader*
Mitchell S. Robinson
Stephen K. Welman
Stanley A. Horowitz
Graham D. McBryde
Matthew S. Goldberg

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IDA
INSTITUTE FOR DEFENSE ANALYSES
1801 N. Beauregard Street, Alexandria, Virginia 22311-1772

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Karen W. Tyson, Mitchell S. Robinson, Stephen K. Welman, Stanley A. Horowitz, Graham D. McBryde, Matthew S. Goldberg

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This paper reports on the development of a new system reliability assessment method, to be used for assessing the tradeoffs between equipment reliability and logistic support resources early in the acquisition process. The purpose is to quantify what reliability buys in terms of lower spares costs and other support costs. Both peacetime and wartime conditions are examined. The method is demonstrated using the F-15C aircraft as a model for a notional advanced tactical fighter (ATF) avionics suite.

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PREFACE

This Paper was prepared by the Institute for Defense Analyses (IDA) for the Office of the Assistant Secretary of Defense (Production and Logistics) (ASD(P&L)), under contract MDA 903 89 C 0003, Task Order T-B7-512, issued 1 December 1988, and amendment. The objective of the task is to develop quantitative relationships between the quality of weapon systems and aspects of their cost, and to investigate methods for predicting the impact of reliability on the support cost and combat availability of new systems early in the acquisition cycle. This represents an interim draft report of the first year of the study work.

This work was reviewed within IDA by Dr. J. R. Nelson, Mr. William Shafer, Dr. Robert Winner, and Dr. Fredrick Riddell.

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EXECUTIVE SUMMARY

A. BACKGROUND AND OBJECTIVE

In the new strategic environment marked by an easing of East-West tensions, defense resources will be increasingly constrained. We will be challenged to make the most of the dollars available. Reliability in weapon systems is often neglected, because any investment in reliability occurs up-front, while the payoff in reduced support costs and increased availability occurs later.

Support cost analysis should be used to examine the cost of alternative ways of achieving specified levels of combat effectiveness. Thus, there is a need for tools to evaluate the value of improved reliability in a wartime context. As with other aspects of system design, the desired level of reliability should be determined through explicit consideration of the environment in which the system is meant to be used. This implies not only using methods designed to reflect the combat environment as closely as possible but also applying the methods to data that reflect as combat-like a setting as possible.

The three military departments are each developing next-generation aircraft that will bring together advanced avionics technologies and design concepts on a new scale. The new avionics technologies on which these aircraft are based promise improved availability and lower support costs, but these features have not yet been rigorously demonstrated in actual flying experience. For these reasons, assessing the value of the new avionics with regard to sortie generation and spares costs is especially important.

This paper reports on the development of a new method for assessing a system's reliability. The method can be used for assessing the tradeoffs between equipment reliability and logistic support resources early in the acquisition process. Our purpose is to quantify what reliability buys in terms of lower support costs and higher mission availability. In order to do this, we examined support under both peacetime and combat conditions.

B. ISSUES

In evaluating the reliability of a new system, many issues must be addressed. The program office usually sets the goals for system and subsystem reliability, the limitations for the system and subsystem cost, and the plans for system maintenance. In addition to evaluating the approximate level of system reliability, the Office of the Secretary of Defense (OSD) must determine whether the maintenance concepts for new systems are consistent with the mission requirements—for example, determining whether a mean time between failures (MTBF) of 3.2 hours is consistent with a four-sortie-per-day requirement. To make these decisions, a review is conducted at the subsystem level, usually at Milestone 1 and no later than Milestone 2. If the maintenance concept for a system is not consistent with mission requirements, then OSD works with the relevant military service to make them consistent.

Theoretically, improvements in the reliability of equipment have two important benefits:

- Program costs are lower. A given peacetime or wartime flying program could be completed at a lower cost for spare parts, manpower, support equipment, etc.
- The capacity to generate sorties is greater. For a given set of support conditions, more missions can be flown. This would be particularly true in the case of substandard logistic support.

In a new program, data about cost and reliability of particular parts are often sketchy or completely unavailable. It would be useful to have a new system reliability assessment method that accepted data in different levels of detail. It would also be helpful if the method could be used to vary assumptions about reliability, cost, and design features. This would make it possible to analyze the implications of achieving goals or failing to achieve them. Perhaps more importantly, it would allow designers to make reliability/cost tradeoffs in an informed way.

Properly considering reliability in design and acquisition of a new system presents a considerable challenge. With a new system, information on costs of components and the potential failure rates is often quite limited, and the architectures are only vaguely specified. Therefore, evaluating a maintenance concept can be extremely difficult.

This paper discusses these problems in the context of a case example—the F-15C and a next-generation tactical fighter. We considered particular issues in the architecture of the new system, such as the increased use of redundancy. We also have taken some initial steps toward considering alternatives for evaluating the impact of reliability on other support costs, not just spares.

The planned advanced tactical fighter (ATF) differs from the F-15 in a number of ways important to reliability analysis. The ATF avionics are being designed to achieve reliability and maintainability; the overall goal for the aircraft is to double the reliability of the F-15. If this goal is achieved, planners hope that the need for the avionics intermediate shop (AIS) can be eliminated, and support costs substantially reduced. The reliability of the avionics suite is expected to be increased both through inherent reliability and through redundancy features.

In the new avionics architectures, redundancy may be implemented beyond the usual flight control systems to include other systems, and some components may be reconfigurable. (Reconfigurability means that a single component can perform the functions of a number of other components—it performs the function that is needed.) Other features that will increase availability include enhanced fault detection and fault isolation, and fewer connectors, which have traditionally been an important source of reliability problems.

Eliminating the AIS has several benefits. There is no need for the expensive, bulky test equipment at the AIS. AIS test equipment is also vulnerable to breakdown of its own, and considerable resources go into maintaining and repairing it. Moreover, eliminating the AIS has substantial readiness benefits. The AIS is vulnerable to attack, and eliminating it eliminates an important target. In addition, squadrons can deploy faster and with fewer cargo aircraft and other resources.

The development process for the new avionics represents an opportunity to demonstrate how the value of reliability in a new system is evaluated. Following a new system from the start of concept definition to initial operational capability (IOC) would allow a good demonstration of the method.

At the time of the study, very little information was available about the expected cost or reliability of ATF equipment. This illustrates the need for a new system reliability assessment method that is applicable under varying conditions of information availability, and which provides a common methodological baseline as information availability improves.

C. APPROACH

1. Model Selection

Since many models have been developed that can link reliability to the sortie-generation capability of a squadron of aircraft, developing a model was not necessary. We chose the Dynamic Multi-Echelon Technique for Recoverable Item Control (Dyna-METRIC) as our analytic tool based on its ability to adequately capture the critical aspects of wartime operations and on its ease of use.

2. Demonstration of the Method with an Existing System

We demonstrated the method with an existing system, the F-15, and found:

- Analysis of the value of reliability requires a look at combat conditions, not just peacetime conditions.
- A high-reliability F-15 flies 33 percent more sorties, at one-third the cost per sortie, in a severe combat case that included battle damage, maintenance delay, and attrition.
- With a more challenging sortie schedule and severe combat conditions, the high-reliability F-15 achieved 358 sorties, while the normal F-15 achieved only 233 sorties.

3. A New System Reliability Assessment Method

The analytic procedure outlined in the preceding paragraphs must be modified to permit analysis of systems that do not yet have firm designs or detailed data on the cost and failure rates of their components. To develop and test such modifications, we analyzed the F-15 as if it were in an early stage of system development and proceeded as if we had only the kind of aggregate information on the reliability of the F-15 and the cost of its components that is typically available at such a stage. In addition to the average failure rate and cost of the components of the system, we assumed the availability of specific information on a small number of critical parts. Disaggregating these into estimates of the costs and failure rates of individual devices is crucial to developing reasonable estimates. It is also critical not just to work with cost and failure rate separately but to consider their joint distribution.

As a first step in using a model to analyze reliability in new systems, we examined how new systems could be evaluated using incomplete data.

4. Demonstration of the Method with a New System

Based on available data, we developed first-order estimates of cost and failure rates for devices in a notional ATF avionics suite. We analyzed the cost of the wartime reserve spares kit (WRSK) under varying conditions. We varied reliability level, cost, and redundancy. Our increased cost excursions are particularly important, since some devices have high-cost risk, and high-cost items fall disproportionately into the low-reliability category. We also examined cases in which the fault detection and partitioning are not optimal, to see how that affected the cost of the WRSK.

5. Analysis of Total Operating and Support Costs and the Cost of Achieving Increased Reliability

When deciding how much quality to demand in new systems, DoD needs the ability to estimate the cost implications of designing and manufacturing higher quality equipment. Moreover, this information is required at an early stage in the procurement cycle, so that design and manufacturing processes may be influenced by the cost tradeoffs.

As part of this effort, we have begun to consider costs and benefits of reliability other than those shown in avionics WRSKs. In our initial simulations of a total operating and support (O&S) cost model, we specified a baseline F-15 and two excursions in ranges similar to those represented as goals for the ATF. In the first excursion, the MTBF of all components was doubled. In the second, reliabilities of major parts of the aircraft were varied differentially—the avionics reliability was quadrupled, the airframe reliability was increased by two-thirds, and the engine reliability was increased by a third.

In these initial simulations, only MTBF was varied. Other characteristics of the aircraft were assumed to be identical to the F-15. For Simulation 1, doubling reliability, the cost of supporting the squadron was 26 percent less than the baseline F-15. For Simulation 2, total costs were 23 percent less than the baseline F-15. This approach is still being developed and refined.

D. CONCLUSIONS

Increasing weapon reliability has considerable benefits. In this analysis, we discussed methods to measure those benefits. The principal measures were the cost of the WRSK—under baseline conditions and also taking account of wartime conditions—and sortie generation.

In every case we examined, higher reliability resulted in better performance. In the F-15 analysis, doubling reliability can cut the cost of the WRSK by more than half.

Sortie generation is also greater for more reliable aircraft. When maintenance delay is included in the analysis, higher reliability results in a 14 percent higher sortie rate, with a 62-percent reduction in spares cost per sortie.

Another issue we explored was how stressful combat conditions affected the value of reliability. The usual planning factors often do not allow for some conditions that are very likely to occur. For example, battle damage places demands on the maintenance system and creates delays and downtime. It was unclear whether reliability might be unimportant when time must be taken to repair battle damage; our analysis indicated that, even with a relatively high level of battle damage, reliability has substantial value. In the most severe combat condition case—one that includes maintenance delay, attrition, and battle damage, higher reliability results in a 33-percent increase in the number of sorties achieved, at less than one-third the spares cost per sortie.

Challenging sortie schedules also underscore the value of reliability. When spares are purchased for a normal sortie schedule and then a more challenging flight schedule is attempted, which may occur if a conflict becomes intense, reliability results in substantially more sorties In the most severe case we examined—a 30-day surge situation with maintenance delay, attrition, and battle damage—the high-reliability fighter achieved 358 sorties, and the normal-reliability fighter achieved only 233, a 54-percent advantage.

We also began to develop a new system reliability assessment method. Our method allows for an initial assessment using only the most general information. As the information expands and improves, the method accommodates it.

We demonstrated the method with notional planning factors for the ATF avionics, a system with both greatly increased inherent reliability and major architectural changes. Our method can be used for making reliability/cost tradeoffs. Of course, uncertainty about the details of the ATF design implies uncertainty about WRSK costs, but out conclusion is that the IDA models and methods can be adapted to assess the reliability of the most important features of these advanced architectures.

In our ATF avionics simulations, sparing costs vary nonlinearly with reliability level. Halving reliability from 21 to 10.5 hours results in spares costs four times as great. Halving reliability from 10.5 hours to 5.25 hours results in spares costs almost three times as great.

In each case we examined, redundancy resulted in higher costs. At very high levels of reliability, this is to be expected. For devices with very few failures, a very reliable system, we would expect it to cost more to carry the spares on board than to keep spares on the shelf. This is consistent with the current planning for the ATF, which includes only a small amount of redundancy. With this method, one could assess the combinations of cost and MTBF for which redundancy makes sense.

We examined cost options in which some very high cost devices are assumed. We found that increasing the cost of the high-unit-cost items alone will disproportionately increase sparing costs because these items tend to have higher demand rates. We also examined a situation in which there are some devices with very high failure rates. We found that, even if high reliability is achieved overall, the presence of a few unreliable parts (e.g., poor partitioning) can more than triple the cost of the WRSK.

If the avionics for the advanced tactical fighter meets its cost and reliability goals (admittedly a big if), WRSK sparing costs appear to be minimal. This raises the issue of repair policy and repair infrastructure. Does it make sense to maintain a repair infrastructure for items that seldom fail?

We have developed a framework for the new system reliability assessment method. This analysis can indicate the benefits of additional reliability, but it does not reflect all the costs or all the cost savings of additional reliability. Examining the cost dimension in more detail is essential, because cost must be balanced against the corresponding benefits.

E. RECOMMENDATIONS

Our recommendations are:

- The new avionics architectures should be evaluated using appropriate techniques that address both cost and availability.
- The services should more carefully consider combat conditions when determining which parts are mission essential and when building spares kits.
- The services should consider instituting more reliability improvement programs. Spares cost savings aside, reliability has substantial payoff in combat.
- OSD should assess the reliability of new systems early in the acquisition process. The new system reliability assessment method illustrated here is potentially useful for this purpose. It can also be used by design teams for making cost/reliability tradeoffs. The government could use the method to do

sensitivity analysis of the impact of not meeting goals for reliability, cost, and fault isolation.

- Additional research to support continued development and experience with the method of assessing new systems should be performed. The method should be expanded to accommodate other equipment types. Missiles are the best candidate for initial work. Computer resources for the method should be kept up to date. The ATF analysis should be continued as better data become available and as planning factors change.
- Operating and support cost models with broader coverage should continue to be analyzed as a supplement to the Dyna-METRIC model. A method of adding the cost of increasing reliability should be added to the analysis.

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I. INTRODUCTION

A. BACKGROUND

One way to improve the value of U.S. defense dollars, at a time when resources are becoming increasingly constrained, is through improved weapon system reliability. Reliability contributes both to lower support costs and to increased weapon system availability. For example, high-reliability aircraft equipment reduces costs by allowing for completion of a given flying program at a lower cost for spare parts, manpower, support equipment, etc. At the same time, it increases sortie-generation capacity by making it possible for more missions to be flown. Despite these benefits, reliability is often overlooked when planning weapon acquisitions because the investment occurs up-front, and the payoff occurs later.

The new avionics technologies being used in the next-generation of military aircraft will afford those aircraft both improved availability and lower support costs. But those features have not yet been demonstrated. Therefore, assessing the value of the new avionics with regard to sortie generation and spares costs is important if we are to make good decisions about how reliable we want the systems to be.

But when an acquisition program is in its early stages, data about the cost of components, the reliability of particular parts, and the specifications of the architectures are often sketchy or completely unavailable. To help assess reliability at this stage, a method that accepts data at different levels of detail would be helpful.

The level of reliability needed for a system should be determined in the context of the environment in which the system is to be used. This means that the methods used must be designed to reflect the expected combat environment and that the data used must reflect a combat-like setting.

In order to effectively assess the value of improving system reliability, tools are needed that allow for examination of reliability under these circumstances.

B. OBJECTIVE

This paper reports on work toward the development of a new method for assessing weapon system reliability. The method can be used early in the acquisition process to assess the trade-offs between equipment reliability and logistic support resources. Our objective was to quantify what improved reliability "buys" in terms of lower spares and other support costs. In order to do this, we examined support under both peacetime and combat conditions.

C. APPROACH

This work was conducted with the use of the Dynamic Multi-Echelon Technique for Recoverable Item Control (Dyna-METRIC), an already existing model that links reliability to sortie-generation capability. We demonstrated the use of the model first with an existing system, the F-15C fighter. We then modified the method used so that we could evaluate the reliability of a system still under development, when little information is available. We used the advanced tactical fighter (ATF) as an example of how the method can be used for a new system.

Because little information was available about the expected cost or reliability of ATF equipment, we estimated the cost of and failure rates for devices in the proposed ATF avionics suite. Using information on F-15 wartime reserve spare kits (WRSKs), we estimated cost under varying levels of reliability, cost, and redundancy. Finally, we began work into the examination of the costs and benefits of reliability other than those shown in avionics WRSKs by simulating a total operating and support (O&S) cost model.

D. ORGANIZATION

We present this work by beginning in the next section with a description of Dyna-METRIC and the data used in our analyses. In Section III, we demonstrate the improved reliability assessment method through the use of the F-15C. We discuss the features of the ATF in Section IV before describing in Section V how we revised our method so that we could demonstrate its use on the ATF. In Section VI, we present the method and results of our excursions into simulating the total O&S model.

II. MODEL AND DATA

A. THE DYNA-METRIC MODEL

The Dynamic Multi-Echelon Technique for Recoverable Item Control (Dyna-METRIC) model is used by the Air Force to develop inventory requirements to meet specified levels of supply readiness (at minimum cost) and to evaluate the readiness and sortie-generation capability of aircraft as a function of logistic support (supply and maintenance) and operational considerations (such as flight scenarios and attrition rates). The model is described in [1] and in Appendix A.

Dyna-Metric was selected for use in this study for the following reasons:

- It is capable of assessing the following determinants of readiness and sortie-generation capability in an integrated fashion:
  - Reliability of aircraft components
  - Dynamic (fluctuating) flight hour programs
  - Dynamic logistic support availability (resupply cut-off and delayed intermediate-level maintenance support)
  - Aircraft attrition.
- It is flexible in terms of data requirements, making it suitable for use throughout the entire acquisition process. Dyna-METRIC can assess baseline reliability and maintainability, alternative aircraft configurations, logistics support characteristics, and force deployment strategies. As improved data on aircraft configuration, component reliability, component cost, maintainability, and logistic support structures become available, data bases can be easily modified for use in the model. While data quality improves, the evaluation technique remains constant. Better data improve the accuracy of model estimates, and use of the same model maintains consistency.
- It has become accepted by a large section of the Air Force community as a tool for evaluating logistic support in terms of sortie generation.
- It is used by the Air Force Logistics Command (AFLC) to determine inventory requirements (such as WRSKs) to meet readiness objectives.
- It is relatively easy to use. Data elements are transparent to decision makers, and model execution is relatively inexpensive and rapid.

Several other models were considered for use in our analysis. They fall into two classes, analytic models and Monte Carlo simulation models.

Dyna-METRIC is an analytic model. This type of model uses established mathematical and statistical theory to develop functions for estimating relevant support and operational statistics such as expected site back orders or fill rates and expected aircraft readiness or sortie success rates based on specified logistic support resource levels. These models are referred to as analytic because of their reliance on equations relating system inputs to system outputs.

Other analytic models are CACI's Availability Centered Inventory Model (ACIM), the Army's Selective Stockage for Availability, Multi-Echelon (SESAME) model, and the Center for Naval Analyses' Multi-Item, Multi-Echelon (MIME) model. Some of these models are deterministic, in that they do not consider the probabilistic nature of the system's behavior. These models differ from Dyna-Metric in that they estimate only the steady-state behavior of the system. Given initial resource levels and a logistic support structure, they assume that operating tempo and support are constant over a long period of time, and they provide evaluation of readiness at a point in time when the effect of support stabilizes.[1]

While all of these analytic models have specialized features that make them attractive for analyzing the effect of resource levels on capability, Dyna-METRIC was selected for use in the IDA study because it is capable of evaluating non-steady-state behavior—fluctuating operating tempo over a specified scenario and fluctuating logistic support associated with temporary cessations in resupply or repair capability.

Monte Carlo simulations can, in theory, replicate all of the operational and support concepts modeled by Dyna-METRIC. They are stochastic models that attempt to model every (programmed) operational, maintenance, and supply event of some scenario through assumed probability distributions and their parameters. Monte Carlo simulation models include the Naval Air Systems Command's Comprehensive Aircraft Support Effectiveness Evaluation (CASEE) model, the Naval Air Development Center's Simulation Package for the Evaluation by Computer Techniques of Readiness, Utilization, and Maintenance (SPECTRUM) model series, and the Air Force's Logistic Composite Model (LCOM).

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1 Dyna-METRIC has a user option that allows steady-state evaluations.

Based on the study team's experience with these models, Dyna-METRIC was selected instead of the Monte Carlo models for use in this study for the following reasons:

- Dyna-METRIC captures the effect of the main areas of logistic support, flight operations, and aircraft parameters (reliability) as well as the available Monte Carlo models when the supporting data have the qualities one would expect to gain through the acquisition process.
- Monte Carlo simulations are typically difficult to use, because they require massive data sets. During the acquisition process most of the detailed resource data available are not always accurate. Establishing the necessary data requires relatively large commitments in time and money, and the results will not surpass the quality of the Dyna-METRIC model output unless the accuracy of the data is guaranteed. Data quality for new systems is expected to be relatively poor prior to Milestone III and is likely to remain so until shortly before the initial operational capability date for a system.
- Monte Carlo simulations are expensive to use because of computer and time requirements. Because of the stochastic nature of Monte Carlo models, hundreds if not thousands of replications of one scenario are necessary to estimate average performance statistics with sufficiently small confidence intervals. Using these models can become prohibitively costly.
- Dyna-METRIC can estimate the spare parts required to meet readiness targets at minimum cost. The Monte Carlo models can only evaluate sortie capability given a set of spares and have no easily executable provisions for estimating requirements.

Dyna-METRIC was selected instead of the Monte Carlo models, because it was judged to provide the same quality output (as related to problems of this study) as the Monte Carlo models, given the quality and the level of detailed data available during acquisition. Moreover, Dyna-METRIC is capable of producing more timely and cost-effective results.

1. What Dyna-METRIC Does

When supplied with line-replaceable unit (LRU) inventory levels, Dyna-METRIC simulates flight operations and resulting supply and maintenance responses. Unavailability of repair parts is recognized by the model as causing "holes" in aircraft (i.e., down aircraft). The Dyna-METRIC provision to allow component cannibalization is used for all LRUs (holes are consolidated). Cannibalization is not allowed for the pseudo-LRUs used to introduce maintenance (delay-LRUs) and battle damage.

Dyna-METRIC can then estimate the expected percentage of aircraft available at any point in the scenario. Using this information with the specified maximum number of sorties per aircraft per day, the model estimates the expected number of planned sorties that can be accomplished at each point in the scenario.

In this way, Dyna-METRIC can be used to evaluate logistic support in meeting a planned scenario. Note that inventory-level specifications must be made for each aircraft component in this analysis.

For the IDA study, Dyna-METRIC was also used to determine inventory requirements. Dyna-METRIC has an optimization routine that uses its evaluation methodology to select an inventory that will meet a readiness objective (a specified not-mission-capable rate due to supply) at minimum inventory cost at a specified confidence level. The inventories developed by Dyna-METRIC for this study were constructed using parameters similar to those that would typically be used by AFLC in inventory requirements development.

When appropriate, additional model features were developed by the study team to enhance the value of the model's output. (These features are briefly described in the following paragraphs and are detailed in Section IIB.) The model has no direct provisions for modeling organizational maintenance delays and battle damage repair delays; however, the study team modified Dyna-METRIC to include these factors in the analysis (also addressed in Section IIB).

When using the Dyna-METRIC attrition option, Dyna-METRIC assumes input operating tempo requirements apply to non-attrited aircraft only. For example, suppose a squadron has 2 aircraft, model input requires three sorties per aircraft per day, and one aircraft is lost to attrition on day 1. On day 1, Dyna-METRIC's simulated squadron attempts to fly six sorties, but on day 2 the model requires only three sorties. Therefore, we had to apply a factor to adjust the sortie goal when the attrition option was used.

Dyna-METRIC has a limited capability to assess the effect of scarce repair resources, such as test benches and manpower on spare part availability. Although the study team did not exercise this feature of the model in the analysis described here, this capability may be used in future evaluations of alternative support structures. If the user does not execute this constrained repair option, the model defaults to assuming infinite intermediate-level repair capability. (Under this model default, one can always assume inputted turnaround times (TATs) reflect support equipment availability. In this case, care must be taken to construct component TATs on this basis.) Regardless of the number of intermediate-level maintenance actions, average component TATs remain constant. In using the constrained repair option, the effect of queueing for scarce resources on pipeline size (or, equivalently, time to repair) is estimated, and the effect of increased pipelines on spare part availability and readiness is estimated by the model. (For a discussion of the limitation of the constrained repair option, see Reference [1].) While IDA has not executed this option during this study and thus cannot evaluate this option, evaluations of support equipment concepts may be possible during early stages of the acquisition process when logistic support is being postulated.

Dyna-METRIC also has a limited capacity to model equipment redundancy. The redundancy concept implemented in Dyna-METRIC is relatively simple. Redundancy is modeled in Dyna-METRIC through the "LRU quantity per aircraft (QPA)" parameter. Associated with this is an optional parameter, minimum quantity per aircraft (MQPA), which characterizes the number of LRUs out of the QPA that must be functioning for the aircraft to be mission capable. Thus, for an LRU with QPA=2, MQPA=1, one copy of the LRU can fail before a single additional failure will make the aircraft not mission capable.

The implementation of a redundancy concept in a model like Dyna-METRIC requires the specification of maintenance rules for mission-capable aircraft that have been degraded through the loss of redundant devices. The maintenance rules specified in Dyna-METRIC are relatively simple. The failure of a redundant device (e.g., a failure that leaves the aircraft fully mission capable) generates a demand that the maintenance system tries to satisfy. The demand may be met from either the existing stock of spares or from the pool of parts cannibalized from other aircraft. However, satisfying this demand has less priority than repairing aircraft that are not mission capable. Thus, a mission-capable but degraded aircraft will neither preclude the repair of one not mission capable nor make a mission-capable aircraft not so.

2. Model Limitations

Dyna-METRIC, like any model of this type, provides assessments of performance on the basis of assumptions made about the general operations of supply, maintenance, and sortie generation built into the model and the relevant data fed into the model. However, the model cannot, for example, take into account the ingenuity of supply and maintenance officers, all of the unobserved or unexpected conditions resulting from wartime operations, or the perturbations in average failure rates and repair times (from planned numbers) that cannot be foreseen. Dyna-METRIC does not model every nuance of aviation support. Nevertheless, it does model aircraft operations and supply and maintenance with sufficient accuracy and detail to allow managers to make effective decisions about support and design parameters for aircraft.

3. Data Requirements

Dyna-METRIC estimates the effects of logistic support on a planned operating scenario. Assuming a specified level of rear-echelon support, Dyna-METRIC is capable of simultaneously analyzing multiple-site operations in a multi-echelon support network. The user must supply the following input to the model to define the planned operating scenario:

- Force levels (number of aircraft)
- Flying hour program
  - Number of sorties per day
    - Peacetime rate
    - Number per day for each day of the wartime portion of the scenario
  - Flight hours per sortie
- Attrition rates (separate rates can be specified for each day of the wartime portion of the scenario).

To analyze operations in terms of logistic support, each aircraft must be described in terms of its components (LRUs) and, if possible, the lower indentured components of the LRUs (shop-replaceable units (SRUs) and sub-SRUs). Analysis conducted in this study focused on LRU-level devices. The following factors are used by the model in analyzing the effectiveness of a logistic support system.[2]

- Aircraft configuration (a complete list of the devices or the components on the aircraft).
- Removal rate for each component (per flight hour or per sortie).
- Quantity of each device or component per aircraft.
- Level of repair for each component (an indication of whether a component can be repaired on site or must be repaired at higher echelons of support, such as depots).
- Not-repairable-this-site (NRTS) rate for each LRU. This is the percentage of removals that must be condemned or sent to higher repair echelons because, for example, the site does not have complete repair capabilities.

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2 If lower identured parts are analyzed, similiar factors must be supplied for the SRUs and sub-SRUs.

- TAT for each LRU. This is the time it takes maintenance to return a failed part to a ready-for-issue state and should not be confused with the time it takes to remove a failed part from an aircraft and replace it with a working part.
- Resupply time for each LRU. This is the time it takes rear-echelon support to meet requirements for parts that fail and cannot be repaired on site.

In addition to these factors, which Dyna-METRIC has been programmed to represent, the model was adapted to analyze the effects of battle damage and maintenance delay. To take advantage of this customized option, the user must supply the following battle damage operating scenario parameters:

- Battle damage rate as the number of battle damage incidents per sortie[3]
- Proportions of damage by cause.

4. Software Requirements

The version of Dyna-METRIC in use at IDA is AFLC's Version 4.4. This version was adopted because it is most consistent with Air Force calculations of WRSKs. Graphic presentation of research results has been enhanced with the use of various off-the-shelf personal computer (PC) software packages. Results of Dyna-METRIC runs are downloaded to a PC. Data are manipulated in a spreadsheet and a presentation graphics package. The data are then available in a much wider variety of formats than provided by the VAX.

B. DATA SOURCES AND MODELING METHODS

This section describes the data used to illustrate the use of Dyna-METRIC in analyzing aircraft reliability. They are presented in terms of the Dyna-METRIC input variables listed in the previous section.

1. Force Levels and Flying Hour Programs

The baseline scenario in our analysis supported 24 forward-deployed aircraft during a 30-day wartime scenario with a flying schedule as shown in Table II-1.

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[3] Current IDA programming of this feature assumes battle damage rates are constant during the wartime scenario, but with additional computer time and analyst intervention, the model can evaluate variations in the battle damage rate.

Attrition rates (when used) were assumed to be 2 per 100 sorties attempted for days 1 through 6 of the scenario and 1 per 100 sorties for days 7 through 30. Battle damage rates (when used) were assumed throughout the scenario to be 10 incidents per 100 sorties.

Table II-1. Flying Programs Used in the Study

Scenario	Total 30-Day Sortie Goal	Day 1-6 Sortie Goal	Day 7-30 Sortie Goal
Baseline	1,018	450	568
Moderate Surge	1,649	450	1,199
Full Surge	2,253	450	1,803

Note: Each sortie is assumed to consume two flying hours.

In this analysis, battle damage was modeled from a maintenance delay point of view, and the effect of the unavailability of repair material was not modeled. In particular, battle damage repair was modeled for eight areas of the aircraft. Probabilities of battle damage and mean repair times were based on data from the Southeast Asia Conflict [2]. Two types of battle damage were considered: damage from small arms fire and damage from high explosives. The probabilities of battle damage in each functional area (given a battle damage incident) assuming small arms or high explosive damage are given in Table II-2. Mean repair times for individual battle damage repair are contained in Table II-3.

Table II-2. Probability of Battle Damage by Type of Threat and Functional Area

Aircraft Functional Area	Small Arms	High Explosive
Structure	.933	.927
Flight controls	.126	.182
Propulsion	.163	.225
Fuel	.153	.309
Power	.047	.309
Avionics	.140	.091
Crew station	.042	.073
Armament	.032	.055

Table II-3. Mean Battle Damage Repair Times (Hours) by Type of Threat and Functional Area

Aircraft Functional Area	Small Arms	High Explosive
Structure	8.4	21.3
Flight controls	30.6	27.7
Propulsion	17.8	157.3
Fuel	5.0	5.0
Power	35.0	652.2
Avionics	5.0	5.0
Crew station	20.0	51.9
Armament	5.0	5.0

The data in Tables II-2 and II-3 were used to describe the implications of the assumed number of battle damage incidents (10 incidents per 100 sorties) and an assumed split between small arms and high explosive battle damage. For the analysis presented in this report, we assumed a 50-50 split, but the model can easily examine any desired split of battle damage between small arms and high explosive threats.

2. Logistic Support Scenario

The logistic support scenario was used as a baseline. Elements such as resupply times and intermediate-level maintenance capability were then varied to test the sensitivity of results to these parameters.

The baseline parameters for logistic elements were as follows:

- No resupply from rear-echelon support points during the 30-day scenario. Spare part inventories were designed to support 30 days of operations and were assumed to be on hand at the beginning of the scenario.
- No intermediate-level component repair capability. For the ATF, we assumed that failed line-replaceable modules will not have even simple repair at the bases. In an earlier study of the F-15C, we allowed simple repair of Remove, Repair, and Replace (RRR) items (as designated by AFLC) to begin any time after day 4 of the scenario. More complex repair of Remove and Replace (RR) components (as designated by AFLC) could not be accomplished at all during the first 30 days. These items typically would be repaired at the depot. However, in this study, the line-replaceable units were conceptualized as generally being too complex to repair at the base. In addition, information was

not available regarding the proportion of devices for which repair provisions will be made.

In excursions from the baseline, component repair capability varies because of requirements for support equipment and personnel. The capability to perform battle damage repair was assumed to commence on day 1 of the scenario. When we included maintenance delay in the scenario, it was assumed to be 2 hours for each LRU.

3. Adaptation of the Model for Organizational-Level Maintenance Delay and Battle Damage

An important factor not programmed into Dyna-METRIC is organizational maintenance. The model was not designed to consider aircraft repair delays caused by organizational-level maintenance on aircraft. While the model does consider repair delay caused by supply support, it assumes that removal and replacement of parts is instantaneous, assuming a replacement spare is available. This can cause the model to overstate sortie-generation capability. IDA has developed a technique to incorporate organizational maintenance into the model. To do so, the mean time to repair (MTTR) for each LRU must be specified. This is the time it takes organizational maintenance to replace the next failed part with a spare before returning the aircraft to mission-capable status.

IDA's modifications of Dyna-METRIC to include battle damage and organizational-level repair time analyses (maintenance delay) and battle damage analyses are through Dyna-METRIC's modeling of LRUs.

Aircraft downtime due to organizational-level repair is modeled by constructing a pseudo-LRU for each LRU in the data base. Each pseudo-LRU has the same failure rate and quantity per aircraft as its associated LRU. The objective is to have a pseudo-LRU fail whenever the corresponding LRU fails. The NRTS rate for the pseudo-LRUs are always assumed to be zero—the pseudo-LRUs must always be repaired at the organizational level by some specified time, the TAT. By assuming the pseudo-LRU stock level to be zero, an organizational-level maintenance delay will occur each time an LRU fails. This delay can be customized to each LRU or can be applied to all LRUs. For illustrative purposes, we have assumed a two-hour delay. Delays in aircraft repair due to battle damage are similarly modeled. Currently, eight functional areas of the aircraft are designated as battle damage LRUs. Failure rates (battle damage rates) are specified for each area. An MTTR is specified and used with battle damage LRUs so that the model simulates battle damage repair and its associated downtime.[4]

4. Adaptation of the Model for Sortie Goal with Attrition

The study team evaluated the capability of a squadron to meet a sortie schedule, independent of attrited aircraft. Early runs of the model made it clear that Dyna-METRIC does not attempt to fly a full sortie schedule when there are attrited aircraft. Therefore, we developed a method to allow Dyna-METRIC to handle a full sortie schedule with attrition. The following example illustrates how Dyna-METRIC input is adjusted to analyze an attrition problem. Suppose a squadron of 24 aircraft is scheduled to fly 48 sorties per day for 10 days with an attrition rate of 1 aircraft per 100 sorties. Table II-4 reflects how Dyna-METRIC input is scaled to analyze this schedule.

Table II-4. Example Method of Optempo Adjustment in Attrition Case

Day	Number of Non-Attrited Aircraft	Planned Number of Sorties	Sorties per Aircraft per Day
1	24	48	2.00
2	24	48	2.00
3	23	48	2.09
4	23	48	2.09
5	22	48	2.18
6	22	48	2.18
7	21	48	2.29
8	21	48	2.29
9	20	48	2.40
10	20	48	2.40

Prior to model execution, a daily squadron sortie schedule was developed for analysis. Based on this schedule and the attrition rates that were to be analyzed, the daily number of non-attrited aircraft were computed. Using the daily numbers of attrited aircraft and the desired daily sortie schedule, the number of sorties per non-attrited aircraft were computed for each day of the scenario. This sortie schedule and the assumed attrition rate were entered into Dyna-METRIC to guarantee an analysis of the desired sortie goal for each day of the scenario.

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4 Analyzing battle damage by component would require that LRU falure rates, MTTRs, TATs, and NRTS rates be adjusted to reflect battle damage. Data are insufficient for this detailed analysis at present.

III. MODELING RELIABILITY IN A CURRENT SYSTEM

This section contains results of computer runs using F-15C data and the Dyna-METRIC model to demonstrate how changes in system reliability affect sortie generation and the cost of spares. The following baseline assumptions were made:

- Sortie program with surge in first six days only (see Table II-1 for details).
- RRR repair beginning on day 5, no RR repair during the scenario.

Our process of analysis was to:

- Buy spares to achieve this baseline scenario, at varying levels of reliability.
- Analyze the cost of these spares.
- Study wartime scenarios by introducing assumptions about attrition, battle damage, and maintenance delay. In each case, begin with sufficient spares to achieve the flying program, under baseline conditions, at each level of reliability. Determine how well the squadron does with these spares packages in each excursion.
- Evaluate the total sorties achieved in each excursion and compare to the baseline.
- Calculate the spares cost per sortie for every scenario.

A. ASSESSING THE COST OF SPARES

The first step in the analysis was to determine the spare parts packages required to achieve the flying program under the baseline assumptions of squadron composition and flying program for the three reliability levels. We consistently used these respective spares packages in conducting the effectiveness analysis of sortie-generation capability.

The total cost of sparing for the baseline flying program was determined for each reliability level. As expected, the costs of the spare parts packages are substantially different under the three reliability assumptions. (See Table III-1.)

Increased reliability dramatically lowered the spares costs of the baseline flight program. The spares costs listed in Table III-1 were used to calculate the spares cost per sortie for each scenario.

Table III-1. Baseline Spares Costs (1985 Dollars)

Level of Reliability	Spares Cost	Baseline Spares Cost per Sortie
Normal (AFLC demand rate)	$69,406,000	$68,200
High (.5 times normal demand rate)	$30,396,000	$29,900
Low (1.5 times normal demand rate)	$106,469,000	$104,600

B. ASSESSING THE EFFECT OF RELIABILITY ON SORTIE-GENERATION CAPABILITY

We evaluated the ability of the squadron to fly the sortie program under a wartime scenario with the following characteristics:

- Organizational-level maintenance delay of two hours for each failure, an approximation of the time required to diagnose and fix the problem.
- Attrition of two percent per sortie during the surge and one percent thereafter, along with maintenance delay.
- Battle damage of ten percent per sortie, along with attrition and maintenance delay.

The line charts in Figures III-1 through III-3 and the data in Table III-2 summarize the results of the evaluation simulations. Each figure shows the number of sorties achieved on each day and at each level of reliability in comparison with the baseline sortie goal. The table shows the cumulative number of sorties achieved by day 6 and by day 30. Spares costs are given in thousands of 1985 dollars.

The case combining battle damage, attrition, and maintenance delay (see Figure III-3) resulted in considerable deterioration in sortie achievement from the preceding cases. By the end of day 6, only 24 percent of sorties could be flown in the normal-reliability case. Reliability made a major difference in the sorties achieved during the surge period. At the end of the 6-day surge, 38 percent of sorties were flown in the high-reliability case, and only 15 percent in the low-reliability case. Reliability continued to play a noticeable role in the number of sorties achieved throughout the last 24 days. In the high-reliability case, 130 more sorties were achieved than in the normal-reliability case over the 30-day period. Overall results for the entire 30-day period under this scenario show that 52 percent of the sorties can be achieved in the high-reliability case as compared to 39 percent in the normal-reliability case and 29 percent in the low-reliability case. A summary of the percentage of the sortie goal achieved under each scenario is presented in Table III-3.

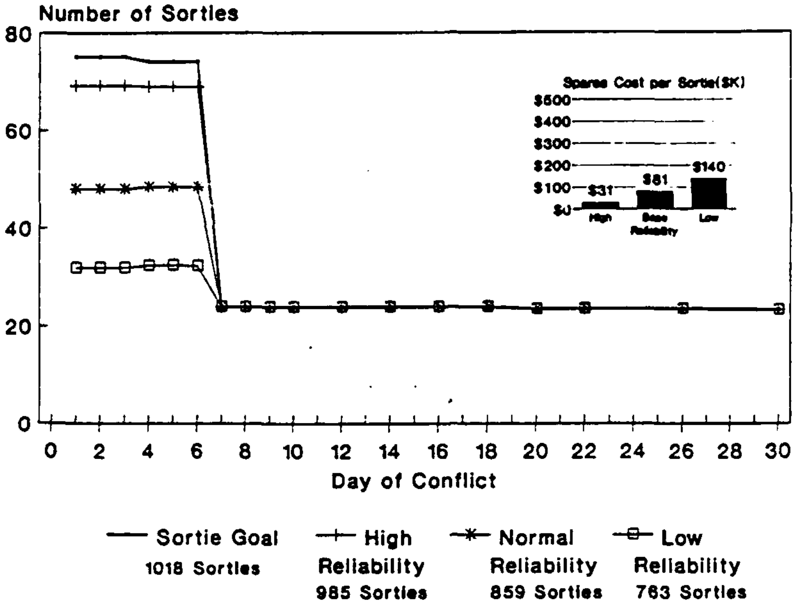

Figure III-1. Number of Sorties Achieved in the Maintenance Delay Case, F-15C, Baseline Flying Program (Spares Costs in Thousands of 1985 Dollars)

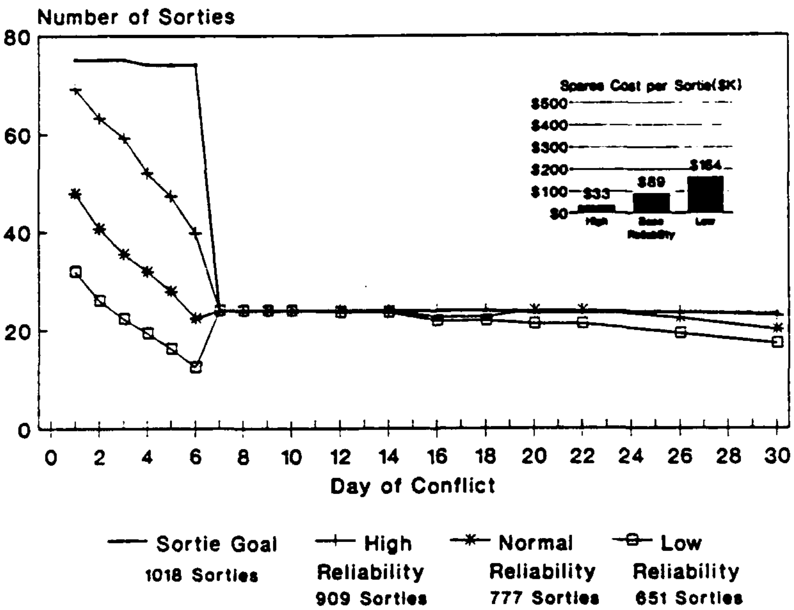

Figure III-2. Number of Sorties Achieved in the Maintenance Delay/Attrition Case, F-15C, Baseline Flying Program (Spares Costs in Thousands of 1985 Dollars)

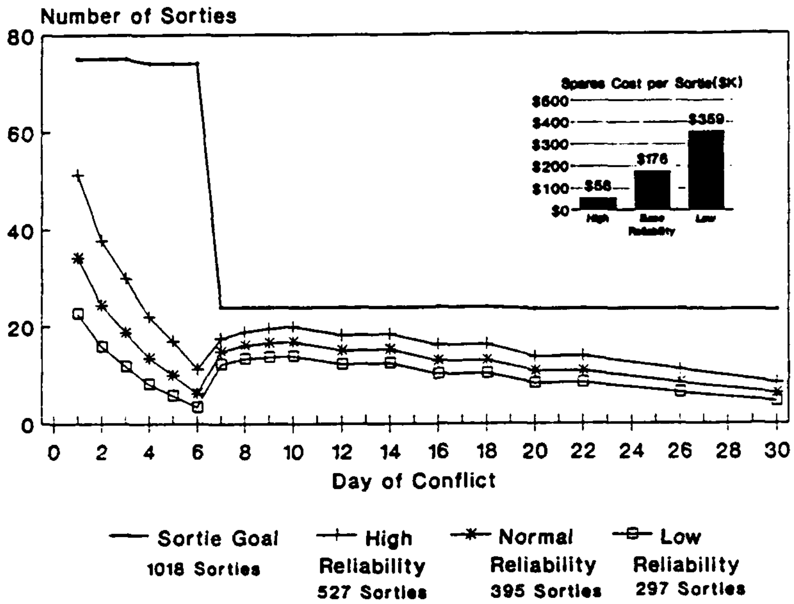

Figure III-3. Number of Sorties Achieved in the Maintenance Delay/Attrition/Battle Damage Case, F-15C, Baseline Flying Program (Spares Costs in Thousands of 1985 Dollars)

Table III-2. Number of Sorties Flown Under Baseline Conditions and Varying Levels of Reliability

	After 6 Days		
	High	Normal	Low
Baseline	448	447	447
Maintenance Delay	415	289	193
Maintenance Delay and Attritition	331	206	128
Maintenance Delay, Attrition and Battle Damage	169	107	68
	After 30 Days		
	High	Normal	Low
Baseline	1018	1017	1016
Maintenance Delay	985	859	763
Maintenance Delay and Attrition	909	777	651
Maintenance Delay, Attrition, and Battle Damage	527	395	296

Table III-3. Percentage of Sorties Flown Under Baseline Conditions and Varying Levels of Reliability

	High	Normal	Low
Maintenance Delay (Sortie goal 1,018)	97%	84%	75%
Maintenance Delay and Attrition (Sortie goal 1,018)	89%	76%	64%
Maintenance Delay, Attrition, and Battle Damage (Sortie goal 1,018)	52%	39%	29%

C. SORTIE GENERATION UNDER MORE CHALLENGING SCHEDULES

Because IDA research results indicated the value of reliability in a wartime scenario, we pursued additional analyses with more severe wartime constraints. We investigated both surge optempo and moderate surge cases under the following conditions using the same parameters as the wartime scenarios:

- No maintenance delay, no attrition, no battle damage
- Maintenance delay only
- Maintenance delay, attrition, and battle damage.

With these sortie schedules, the sortie goals increase (see Table II-1). In the surge case, the sortie goal over the 30-day flying program is 2,253; in the moderate surge case, the total goal is 1,649. Since the demands are now greater, the simulated squadron tries to meet those higher demands. In some of the surge scenarios, therefore, more sorties are achieved than in the baseline flying program.

In some of these simulations, spares stocks were depleted before the end of the 30 days, and no additional sorties could be flown. This is attributable to the fact that at no time in the 30-day scenario do we have repair capabilities at the Air Force's RR level, the more complex repair. In addition, no transportation component is built into the Dyna-METRIC model. Therefore, if initial spares are completely depleted, resupply is not possible.

In this paper, the daily moderate surge sortie achievements are presented graphically, since we used a moderate surge scenario for our simulated ATF avionics suite. Both moderate and full surge results are summarized in Table III-4. All these results are presented more fully in IDA Paper P-2251 (see Reference [3]).

Table III-4. Number of Sorties Flown Under Surge Scenarios

Conditions	After 6 Days		
	High	Normal	Low
Moderate Surge—no Maintenance Delay, no Attrition,no Battle Damage	451	451	449
Surge Optempo—no Maintenance Delay, no Attrition, no Battle Damage	451	450	449
Moderate Surge—Maintenance Delay Only	415	288	191
Surge Optempo—Maintenance Delay Only	415	288	191
Moderate Surge—Maintenance Delay, Attrition, and Battle Damage	196	130	87
Surge Optempo—Maintenance Delay, Attrition, and Battle Damage	196	130	87
Surge Optempo—RRR on Day 10	448	432	399
	After 30 Days		
	High	Normal	Low
Moderate Surge—no Maintenance Delay, no Attrition, no Battle Damage	1613	1308	1027
Surge Optempo—no Maintenance Delay, no Attrition, no Battle Damage	1328	828	685
Moderate Surge—Maintenance Delay Only	1578	1137	723
Surge Optempo—Maintenance Delay Only	1262	581	327
Moderate Surge—Maintenance Delay, Attrition, and Battle Damage	562	413	303
Surge Optempo—Maintenance Delay, Attrition, and Battle Damage	358	233	149
Surge Optempo—RRR on Day 10	1035	493	408

The value of increased reliability is consistently evident throughout both scenarios. If you spare for a baseline scenario but try to fly a moderate surge, you cannot achieve the entire sortie goal in any event. However, with high reliability, you can achieve 98 percent of the goal. (See Figure III-4.) With low reliability, you are down to 62 percent. Each successively higher reliability level buys you approximately 300 more sorties.

With a surge goal, the differences are even more substantial. High reliability allows you to achieve 59 percent of your goal and to keep flying at least some of the program until day 30. Normal reliability gives you 500 fewer sorties and results in no flying capability after day 20. Low reliability gives you 643 fewer sorties, and results in no flying capability after day 14. (Tables II-8 and II-9, in Reference [3].)

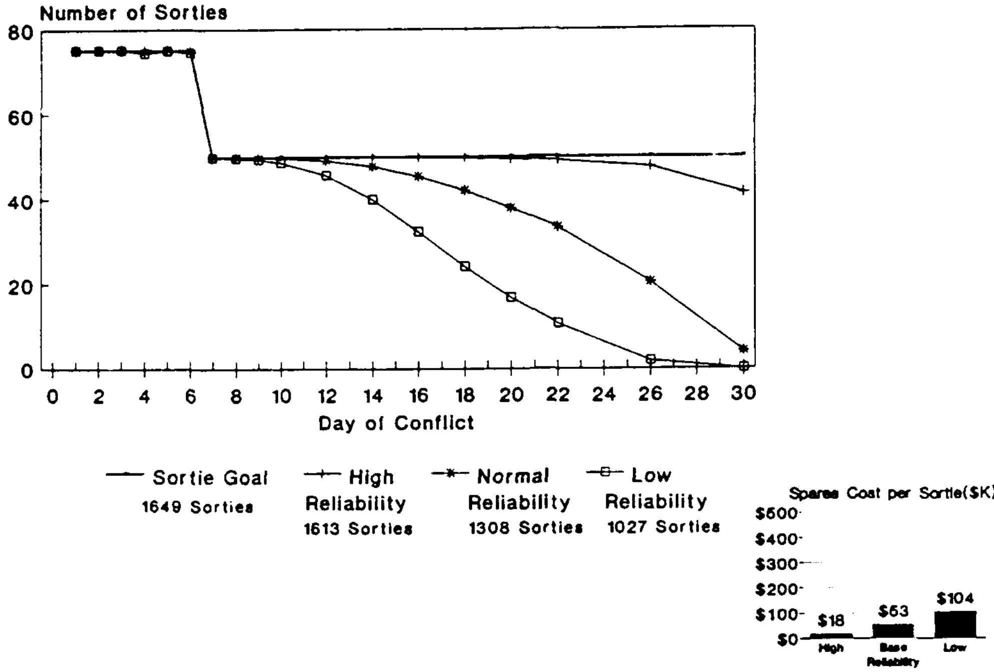

Figure III-4. Number of Sorties Achieved Under Moderate Surge–No Maintenance Delay, No Attrition, No Battle Damage (Spares Costs in Thousands of 1985 Dollars)

Under maintenance delay conditions, the moderate surge scenario results again indicate the value of reliability. In the high-reliability case, 96 percent of the sorties can be achieved, with only 69 percent in the normal and 44 percent in the low-reliability case (Figure III-5). In the surge optempo scenario, sortie achievement drops drastically, with only 15 percent of the goal achieved in the low-reliability case. However, in the high-reliability case, 56 percent of the goal can be achieved, and at least some flying capability exists for the entire 30 days. (Tables II-8 and II-9, in Reference [3].)

It can be observed that more sorties are achieved at each reliability level in the moderate surge case than in the surge optempo case. These results might imply that more sorties can be achieved by requiring less. However, since fewer sorties are required after day 6 in the moderate surge case, there is more time between sorties and the maintenance delay has less effect than it does under surge optempo. It should also be recalled that aircraft are being lost more rapidly in the surge optempo case because we are attempting to fly more sorties to meet the higher sortie goal.

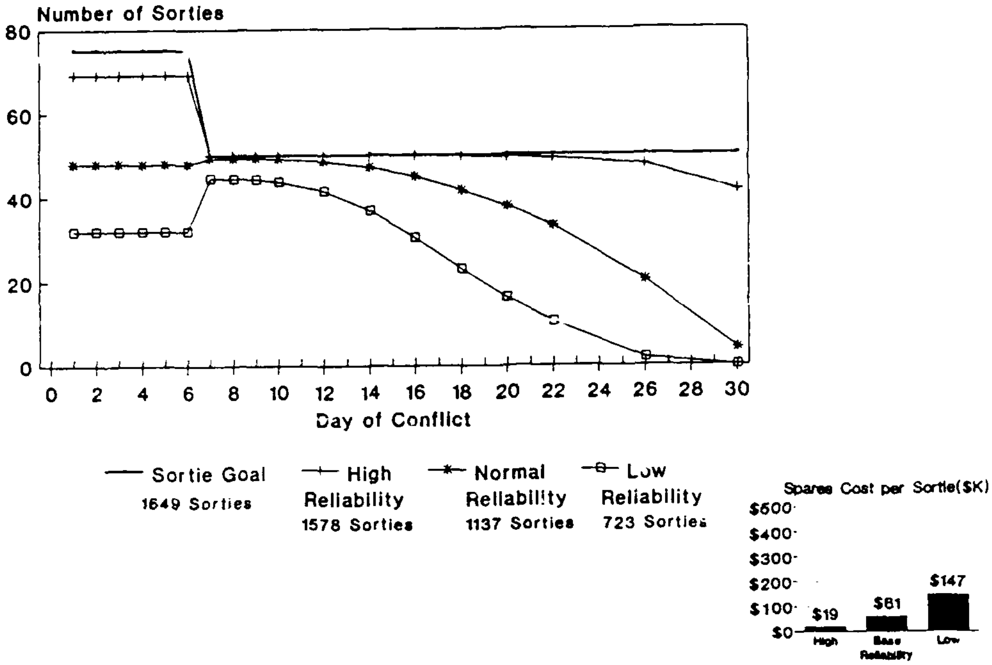

Figure III-5. Number of Sorties Achieved Under Moderate Surge–Maintenance Delay (Spares Costs in Thousands of 1985 Dollars)

The value of reliability is consistently observable in all of the severe cases described here. Figure III-6 and Table III-4 summarize the results of the scenarios with the most severe constraints, moderate surge and surge optempo with maintenance delay, attrition, and battle damage. In the moderate surge, the percentage of sorties achieved at the high-reliability level is only 34, with only 25 for the normal-reliability case and 18 for the low reliability case.

High reliability buys you 259 more sorties than low reliability and 149 more sorties than normal reliability. Sortie achievement under the surge optempo varies from 16 percent for high reliability, 10 percent for normal, and 7 percent for low. Although these are not very positive results, flying a reasonable number of sorties during the first six days is possible, if absolutely necessary. High reliability buys you 209 more sorties than low reliability and 125 more sorties than normal reliability.

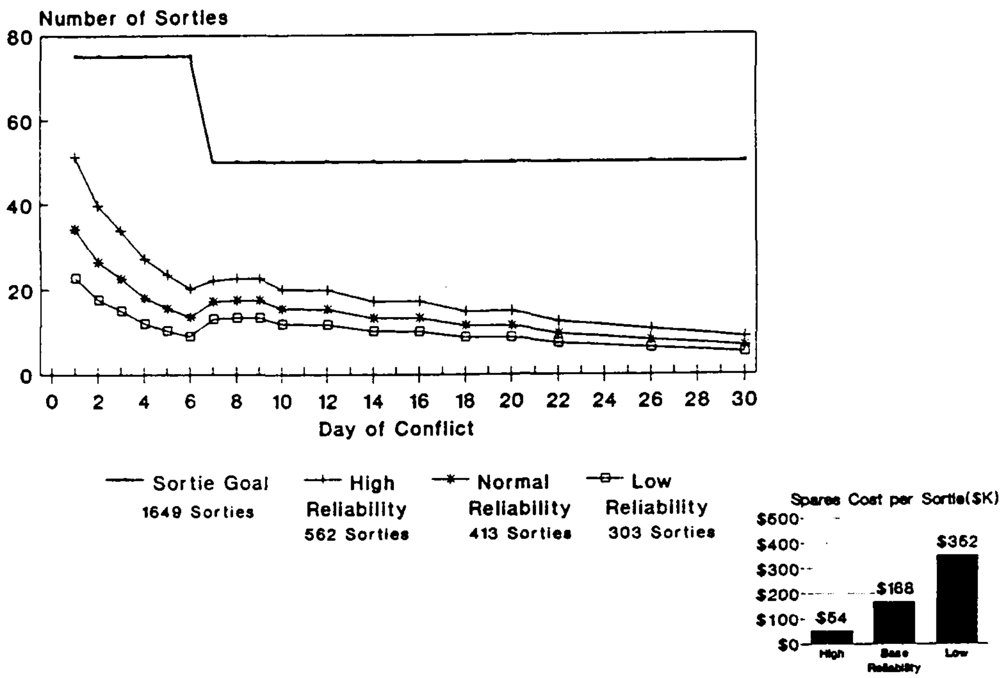

Figure III-6. Number of Sorties Achieved Under Moderate Surge–Maintenance Delay/Attrition/Battle Damage (Spares Costs in Thousands of 1985 Dollars)

D. ASSESSING THE SPARES COST PER SORTIE

The spares cost per sortie was chosen as one measure of the effect of reliability on the cost of the flying program. The spares cost per sortie was computed by dividing the spares cost of a given reliability level by the number of sorties achieved at that reliability level for each study case.

With each set of conditions, the level of reliability makes a substantial difference in the spares cost per sortie. In the high-reliability cases, spares cost per sortie is from 62 to 68 percent less than the spares cost per sortie in the normal-reliability cases. Even greater disparity exists between spares cost per sortie of the normal and low-reliability cases. The low-reliability costs are from 70 to 104 percent greater than the normal-reliability costs. The spares cost per sortie increases at every reliability level as each scenario becomes more demanding. Table III-5 summarizes all spares costs per sortie, which are given in thousands of 1985 dollars).

Table III-5. Spares Cost per Sortie (Thousands of 1985 Dollars) Under Different Conditions and Varying Levels of Reliability

	Level of Reliability		
	High	Normal	Low
Base Case	30	68	105
Maintenance Delay	31	81	140
Maintenance Delay and Attrition	33	89	164
Maintenance Delay, Attrition and Battle Damage	58	176	359
Moderate Surge—no Maintenance Delay, no Attrition, no Battle Damage	19	53	104
Surge Optempo—no Maintenance Delay, no Attrition, no Battle Damage	23	84	155
Moderate Surge—Maintenance Delay Only	19	61	147
Surge Optempo—Maintenance Delay Only	24	119	325
Moderate Surge—Maintenance Delay, Attrition, Battle Damage	54	168	352
Surge Optempo—Maintenance Delay, Attrition, Battle Damage	85	298	714
Surge Optempo—RRR on Day 10	29	141	261

E. CONCLUSIONS

In summary, increased reliability produces higher sortie achievement rates and lower spares costs per sortie in the baseline case as well as under conditions that pose more challenging threats to aircraft availability and have more demanding sortie requirements.

IV. THE CASE OF MODULAR AVIONICS: ARCHITECTURAL FEATURES

A. NEW ARCHITECTURES

The three military departments are each developing next-generation aircraft that will bring together advanced avionics technologies and design concepts on a scale new to operational systems. The new avionics technologies on which they are based promise improved availability and lower support costs, but have not yet rigorously demonstrated these features in actual flying experience. For these reasons, assessing the value of the new avionics with regard to sortie generation and spares costs is especially important.

Specific information on the aircraft programs is generally unavailable because the programs are classified or the aircraft have not yet entered full-scale development. Nonetheless, the design features that planners will exploit to achieve availability and support cost goals have been discussed in the open literature. Further, officials at the LH and ATF program offices have discussed their general quantitative goals for these critical design features with us. Thus, a notional, advanced aircraft can be characterized in sufficient detail for the sake of our analysis.

The remainder of this section characterizes the significant reliability and maintainability features of next-generation aircraft and their predicted effects on availability and support costs.

B. RELIABILITY

The reliability of the ATF avionics suite is expected to be increased both through inherent reliability and through redundancy features.

A significant increase in the *inherent reliabilility*[5] of avionics equipment is expected to be the dominant reliability feature in next-generation avionics. For example, as a subsystem, the F-16's APG-66 radar has an observed MTBF of approximately 200 hours, an order of magnitude greater than the F-4C Phantom II's radar and more than twice that

[5] By *inherent reliability* we are referring to the time between failures of equipment at the level of the line replaceable unit. Failures of components within the equipment is beyond the scope of this work.

observed for the F-15A's radar [4]. The mean time between critical failure (MTBCF) planned for an ATF's active aperture radar is an order of magnitude greater than that of the APG-66 radar. Designers of the next generation of systems seek a substantial increase in equipment reliability from the aircraft currently in the inventory.

The strategies for achieving large increases in reliability vary with the equipment under consideration, though generally they will include the following:

- Reducing environmental temperatures
- Making maintenance-induced failures less likely
- Replacing analog devices with digital devices
- Using VHSIC-generation (very high-speed integrated circuits) microcircuits with a limited capacity for self-repair
- Improving the design/production process through the use of concurrent engineering [5].

The design of next-generation aircraft will also include redundancy at the line-replaceable-module level as a means of reliability improvement. However, at this level, the concept of reliability is not focused on individual equipment but rather avionics functions, as embodied in the concept of fault tolerance.

Fault tolerance is the capacity of a system to continue providing a function (such as inertial navigation) despite the loss of equipment that normally supports the function (ignoring fault tolerance in the software domain). Three kinds of hardware redundancy strategies can be implemented to provide fault tolerance: hardware repetition, "hot sparing," and reallocation of functions.

Hardware repetition involves collectively providing an avionics function with a set of n identical devices that all operate during a mission. If one device fails, the remaining $n - 1$ continue to provide the avionics function. This redundancy strategy appears in the U.S. Air Force's Ultra-reliable Radar, a variant of which may be used in the ATF. Hundreds of identical transmit-receive (t-r) modules collectively replace a single, conventional transmitter-receiver, except that the failure of a small number of t-r modules does not significantly degrade the radar's total performance under specified conditions as would the loss of a conventional transmitter-receiver. Another U.S. Air Force system that implements this redundancy strategy is the ALQ-184 electronic countermeasures pod. Multiple minitube transmitters collectively replace a single, conventional transmitter in the ALQ-184, so the loss of a small number of the minitube transmitters leaves the system relatively intact. Fly-by-wire flight control systems of such contemporary aircraft as the

F-16 and the F/A-18 represent another variation of hardware repetition. All flight control systems function during normal operations, and the loss of any one or two of them does not affect the aircraft's overall performance.

Hot sparing, a second type of redundancy, involves backing up a device with one or more nonoperative spares. Hot spares are run during a mission and so accumulate flight hours toward their own failure; however, unlike hardware repetition redundancy, a hot spare functions only when it assumes the functions of a failed device.

A third type of redundancy, reallocation of function, involves shifting the functions of a failed device to some other device(s). This strategy differs from hot spares in that they are already providing other functions for the aircraft. Reallocation of function may thus degrade the aircraft's performance, depending on the number and concurrency of the demands the aircraft and pilot make on the substituting device, the substituting device's inherent capacities, and what methods the device uses for handling simultaneous demands.

We can model increases in inherent reliability by using Dyna-METRIC. We have also modeled the first two types of redundancy using Dyna-METRIC features. Modeling of reallocation of function would require additional model development and is not attempted here.

C. MAINTAINABILITY

Maintainability complements reliability, with respect to aircraft availability and sortie-generation capacity. High reliability keeps an aircraft flying, and high maintainability ensures that an aircraft is quickly returned to the flightline once a part has failed or is damaged. The maintainability features of next-generation aircraft important to availability and to maintenance requirements are based on four main design concepts: (1) the line-replaceable module (LRM), (2) accurate fault isolation, (3) accurate fault detection, and (4) commonality.

LRMs are to be designed for two-level maintenance, in order to eliminate the avionics intermediate shop (AIS), with its attendant costs and risks. In order to do this, LRMs have to be more like SRUs than LRUs in their physical and functional size. Designers expect to substantially replace LRUs with LRMs in the ATF as the unit of flightline maintenance. However, the full benefits of the LRM concept depend on fault isolation—being able to diagnose accurately where a fault is occurring.

VHSIC-generation microelectronics will allow designers of next-generation aircraft to install more extensive self-test facilities on next-generation aircraft than has been previously possible. However, with ubiquitous built-in test and diagnosis, the challenge facing planners of next-generation aircraft is the more difficult task of designing capabilities for accurate fault detection and fault isolation.

Fault isolation can be achieved at the flightline only to the LRU level with current aircraft. Failed LRUs must then be sent to the AIS, which is deployed with the squadron. At the AIS, faults are isolated to the SRU level. With the LRM concept, plans are to provide the aircraft with an inherent capability for fault isolation to the LRM. The result is replacement of the LRU with the LRM as the unit of flightline fault isolation and maintenance and a substantial reduction in the requirement for a facility to repair and maintain LRU-sized devices.

Eliminating the AIS may offer benefits in several areas of interest in design tradeoff studies. Foremost among them are potential savings in mobility resources required for squadron deployment and support resources necessary for maintaining the AIS. Eliminating the AIS may also reduce the vulnerability of the deployed squadron by eliminating a target important to sustained sortie generation.

Even without substituting LRMs for LRUs as the unit of flightline maintenance, an accurate fault isolation capability has identifiable advantages. Fault isolation accuracy is measured in terms of the number of line replaceable devices in the ambiguity group, the set of line replaceable devices that includes a failed device. Because the fault cannot be isolated beyond the ambiguity group, all members of the ambiguity group must be removed, even though it may contain one or more functioning devices. Therefore, fault isolation accuracy directly affects spares requirements. In addition, because functioning devices may be damaged when they are removed (maintenance-induced faults), the size of the ambiguity group can indirectly influence spares requirements. Designers of next-generation aircraft hope to make the aircraft's built-in diagnostics capable of fault isolating to ambiguity groups of one at least 90 percent of the time and to ambiguity groups of no more than two almost all the time.

Accurate fault detection is a major goal of the new avionics. While the rate of correct fault detection can be increased by lowering a detection threshold, this method inevitably increases the number of false alarms reported. The challenge is to design systems that simultaneously attain high correct-detection rates and low false-alarm rates.

Fault detection goals for next-generation aircraft are detection of 95 percent of all faults of interest with only a 5-percent rate of false alarms, compared with historical rates of over 20 percent.

Commonality has the goal of reducing the numbers of spares types required for an advanced aircraft, by satisfying a given avionics functional requirement with a single type of LRM as often as possible. For example, each of an aircraft's avionics functions (flight control, radar, communication, navigation) may have a common power supply requirement. The design concept, commonality, would dictate using a single type of LRM to satisfy the common power supply requirement wherever possible. This design practice also seeks to standardize the use of LRMs across different aircraft for the same requirements (power supply, bulk memory, data processing).

Designers believe that commonality will simplify aircraft maintenance by reducing the number of spares types and maintenance tool types required. Commonality and standardization are also expected to provide production cost advantages because of the economical production rates. Large quantity requirements for standardized LRMS will also result in savings due to learning.

Designers are also anticipating several other benefits that are enabled by accurate fault isolation and the adoption of common LRMs. The most significant benefit is probably a reduction in maintenance personnel requirements for a given level of aircraft availability. Because of commonality and improved fault isolation fewer types of maintenance personnel will be required.

V. MODELING RELIABILITY IN A NEW SYSTEM

A. BACKGROUND

A main objective of this analysis is to develop a method for evaluating increased system reliability for new systems, early in the design stage when reliability levels can be relatively easily changed. In addition to evaluating system reliability, the Office of the Secretary of Defense (OSD) must determine whether the maintenance concepts for new systems are consistent with the mission requirements—for example, determining whether a 3.2-hour mean time between failures (MTBF) is consistent with a four-sortie-per-day requirement. To make these decisions, a review is conducted at the subsystem level, usually at Milestone 1 and no later than Milestone 2. If the maintenance concept for a system is not consistent with mission requirements, then OSD works with the relevant service to change the requirements.

In evaluating the reliability of a new system, many issues must be addressed. The program office usually sets the goals for system and subsystem reliability and the cost limitations for the system and subsystem. The program office also sets the plans for system maintenance.

The evaluator must then decide whether the goals set by the program office are reasonable and if achievement of the goals will ensure adequate mission performance. The evaluator must also determine whether the maintenance concept, given the goals, is the most cost-effective method, consistent with mission requirements.

Answering these questions about a new system presents a considerable challenge. With a new system, information on costs of components and the potential failure rates is often quite limited, and the architectures are only vaguely specified. Therefore, evaluating a maintenance concept can be extremely difficult. Three factors affect the evaluation process:

- Level of data available. At a very early point in the program, data might consist of only the number of modules, the average cost, and the average failure rate systemwide. Later, data might consist of this information along with specific data on classes of items, such as low-risk, off-the-shelf items. At some later point, more accurate information will become available on the significant cost driving equipment (e.g., the high-cost, high-failure-rate items), along with some indication of the differences among airframe, engine, and avionics. In even later stages of the program, the data would include specific information on all of the equipment.

- Subsystems considered. As the progam matures, we would move from a broad analysis of the entire aircraft, to some detail at the subsystem level, a complete specification.
- Scope of costs considered. Currently, IDA is considering mainly spares costs at a preliminary level. In the future, we hope to include a broad analysis of manpower and support equipment costs. A more complete analysis would model these costs in greater detail.

A preliminary evaluation of the value of reliability in a new system can be done with knowledge of only the number of components in the system, average component cost, and average component reliability. A method developed by Ince and Evanovich (Reference [6]) involves developing a numerical description of a joint frequency function for unit costs and failure rates based on actual data from a similar system. This is important, because the correlation between cost and failure rate has been found to greatly affect the results.

Ince and Evanovich [6] addressed the problem of estimating the spares costs required for a new system to attain a stated level of operational availability (A_O). In the context of a specified scenario (i.e., flying program, threat environment, repair parameters), Ince and Evanovich provided unit cost and reliability data to a computer-based sparing model that yields values for A_O and sparing cost. In order to reduce the dimensionality of the database they substituted failure rate weighted by the multiplicity of unique components in the system (extended failure rate) for separate failure rate and multiplicity statistics.

As part of their analysis they observed that the correlation between the unit cost and the failure rate of aircraft components, as well as higher order moments of their joint distribution, has a significant effect on the cost of spares required to achieve a given level of A_O. Thus, they concluded that the dependency between unit cost and extended failure rate expected for a new system should be represented in order to accurately assess the relationship between A_O and sparing cost.

Because detailed data on the new system may not be available during early stages of development, a suitable model data set is necessary. It is unlikely that an existing system will have the same number of components as the new system. Thus, they developed a more general approach to providing a suitable model data set.

Ince and Evanovich's approach consisted of separately partitioning the ranges of component unit cost and extended failure rate of an existing system into eight categories. The system chosen was one deemed to be globally analogous to the new system of interest. They then recorded the relative frequencies of components falling into each of the 64 unit cost/extended failure rate categories. This aggregate model of the dependency between unit cost and extended failure rate can then be treated as a baseline for the new system, and modified to be consistent with the known characteristics of the new system. For instance, if the existing system consists of 200 components, then the number of parts in each unit cost/extended failure rate cell can be doubled to provide a simulated data set for a new system having 400 components. Alternatively, if it is known that the baseline will differ from the new system due to additional high unit cost/high failure rate items, then the 200 additional items can be added to unit cost/extended failure rate categories thought to represent these attributes.

B. SYNTHETIC DATA: A STEP TOWARD EVALUATING NEW SYSTEMS

As a first step in using a model to analyze reliability in new systems, we examined how new systems could be evaluated using incomplete data. Figure V-1 depicts the methodology that we developed. The key step in the methodology is the development of a synthetic data base to represent the new system.

When only mean costs and failure rates are known, the entire data set is simulated. As more information about the cost and reliability characteristics of individual parts becomes known, these parts are incorporated into the data base. The rest of the modules in the system are simulated in a way that keeps aggregate system parameters consistent with what is believed about the average cost and failure rate and with the hypothesized joint distribution. Information about critical architectural features of the new system (such as the extent of redundancy among modules) can also be incorporated. As the full configuration of the new system becomes known, the methodology approaches a standard application of Dyna-METRIC.

The synthetic data base is used in exactly the same way we used the actual F-15 data in Section III. A spares package is developed to allow completion of a specified 30-day sortie profile. The ability to fly alternative sortie profiles with this spares package under various assumptions about logistic support, battle damage, and attrition is then analyzed.

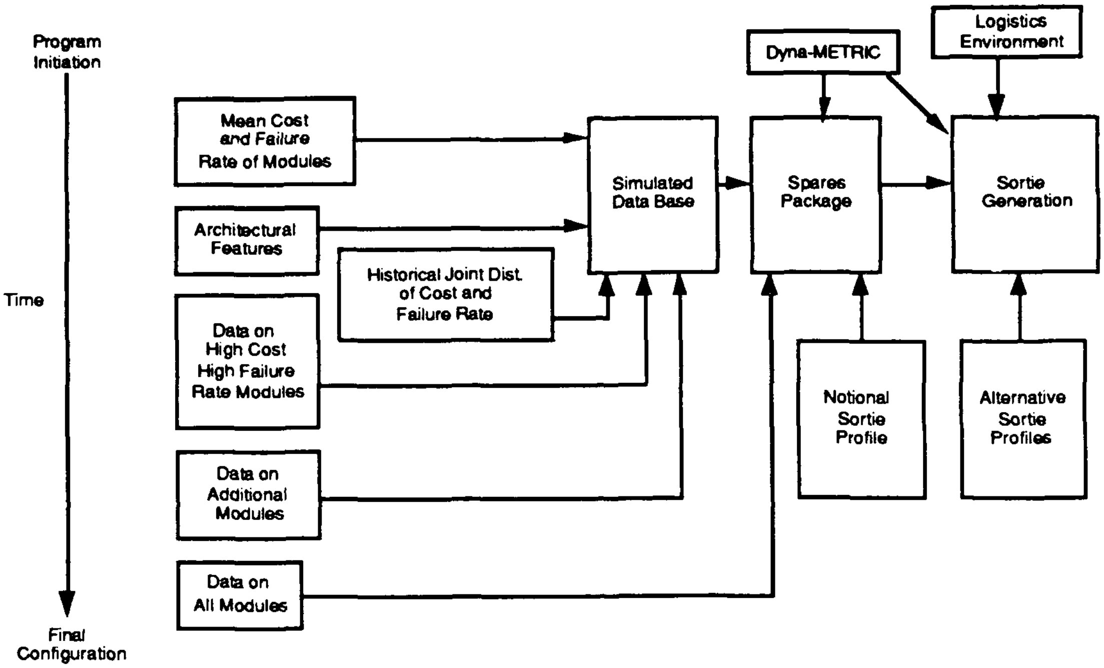

Figure V-1. A Method for Evaluating New Systems

C. METHODS FOR EVALUATING THE EFFECT OF NEW TECHNOLOGY ON SORTIE GENERATION AND SUPPORT COSTS

The development process for the new avionics represents an opportunity for a case example to demonstrate the evaluation of the value of reliability in a new system. Following a new system from its start of concept definition to initial operational capability (IOC) would allow a good demonstration of the method.

1. Simplest Analysis: System Level

The simplest analysis that might be considered involves excursions from our F-15 estimates. The goals for ATF system reliability are broadly consistent with the Air Force's "Double R-Half M" initiative—double reliability, half maintenance. Our approximation of the ATF here represents the case of achieving the reliability goals uniformly across subsystems. These results indicate that increased reliability has a major effect on the ability to fly sorties. This effect increases as the stress placed on the scenario (in terms of challenging sortie schedules, maintenance delays, battle damage, and attrition) increases.

This simple analysis, however, has some serious limitations. First, it assumes no change in underlying technology. The costs of LRUs are assumed to remain the same, i.e., the increased reliability has been achieved without additional cost. This is conceivable; some evidence suggests that concurrent engineering can result in enhanced quality at the same or even lower cost [5]. However, more reliable components may result in greater cost.

In addition, costs for manpower and support equipment may also change, a possibility not considered in this simple analysis. Finally, the F-15C data base used in our analysis does not consider most of the engine and some of the airframe components, because these parts are separately supported or are not part of the Air Force's WRSK.

Another limitation of this analysis is that it assumes that the increased reliability is achieved across the board, not by varying the reliability of individual components, which may be a more efficient way to achieve it.

Nevertheless, this simple analysis provides an initial look given little information.

2. More Detailed Analysis: The Simulated Data Method

The simulated data method developed by Ince and Evanoich [6] also requires relatively little data—knowledge of only the number of devices of interest, their average cost, and their average failure rate. If these data are available, a simulated data set can be developed at the LRU level, using a distribution from a similar system.

A method for describing the distribution of devices in terms of cost and failure rate means was demonstrated in References [3] and [6]. In the former study, F-15C LRUs were partitioned into an 8-by-8 matrix using the following ranges based on the mean m:

- 0 to m/8
- m/8 to m/4
- m/4 to m/2
- m/2 to m
- m to 2m
- 2m to 3m
- 3m to 6m
- Greater than 6m.

To construct the simulated data set, LRUs in each cell were assigned the midpoint of the cost and failure rates in each cell. In addition, actual values of the 13 high-cost, high-failure-rate items were assumed to be known. Using this data set to estimate WRSK costs resulted in overestimates in each case. Nevertheless, the *relative* magnitudes for the low-, normal-, and high-reliability cases appeared reasonable. In addition, the sortie generation results were reasonable.

3. Modifying the Method to Deal with the Realities of Data Availability

The simulated data method described above in Section C2 has some disadvantages. It is inflexible with regard to partial information already available about cost or failure rates (e.g., the average unit cost of some set of devices has been accurately estimated). In addition, this method does not allow the user to shape the distribution of costs or failure rates within categories. Experience may show that intra-category distributions with different kinds of characteristics (e.g., degree of variability, symmetry/skewness, kurtosis) may be preferred among different category types (e.g., categories at extremes, in the middle, in a truncated tail, in a long tail) may yield more accurate estimates. Similarly, cost and failure rate distributions of different types may require more or less densely distributed categories over their range to support more accurate estimates (e.g., more categories in a long tail than around the mode of the distribution).

In the study of the ATF avionics reported in the next chapter, we chose to modify the Ince-Evanovich method to make the best use of the data we had available to us. In our case, while we could make a reasonable guess as to the grand mean unit cost, we could not find an approximation of the grand mean failure rate. In addition, our information sources did not have data which allow classification of devices in terms of categories defined with respect to the grand mean. The more flexible partitioning scheme we adopted allows for greater control over category construction in this regard. This partitioning is described in the next section.

VI. COST OF SIMULATED ATF MODULAR AVIONICS WRSKS UNDER VARYING CONDITIONS

A. INTRODUCTION

At the time of the study, very little information was available about the expected cost or reliability of ATF equipment. This illustrates the need for a method that is applicable under varying conditions of information availability, and which remains constant as information availability improves, providing a common methodological baseline.

The sparseness of information prompted us to limit the detail of the analytical data base to only a coarse level of grain. The IDA methodology described in our earlier paper must be extended to apply it to the new aircraft currently under development. For example, we did not consider redundancy features in our study of the F-15. Further, we varied the reliability of the aircraft's components within a range less than that anticipated for next-generation aircraft. Finally, our study of uncertain LRU costs and failure rates involved a greater knowledge base than will be available for systems still in the early stages of development. In the F-15 case we constructed eight categories of LRU costs and of LRU failure rates, yielding 64 cost-by-failure rate component types. The two sets of categories were developed around the grand mean unit costs and grand mean failure rates.

In fact, the data necessary to develop even such a limited framework proved not to be available. Therefore, we modified our methodology to account for the new features of next-generation aircraft and the realities of information availability. At the time of our analysis, only three levels of both equipment reliability and unit cost (i.e., high, medium, and low) could be identified with confidence. (A fourth cost category, very high, might be appropriate for small-quantity, exotic equipment. At the time of the study we had no information that would have enabled us to use this additional category. However, the high-cost excursions of our analysis presented later address this issue.)

Thus, this early analysis generalized the method used in the IDA study of the F-15C to a three-by-three classification of equipment into cost-reliability categories.

B. ASSUMPTIONS

We were able to develop estimates of several kinds of information required for a Dyna-METRIC analysis, through conversations with officials in the ATF and LH System Program Offices, members of the Joint Integrated Avionics Working Group, and members of the contractor teams. In some cases they were unable to provide specific estimates, but were able to provide a range within which the required estimate might fall.

The ATF avionics suite is likely to consist mostly of LRMs. However, there may be some devices that look more like traditional LRUs and SRUs. In order to encompass all of these, use the term "devices" in our modeling work.

Unit cost figures for avionics devices were estimated at \$7,000, \$14,000, and \$23,000 in current dollars for the low, medium, and high categories respectively. In addition, we also received some guidance on the number of devices constituting the subject system and on the percentage of devices falling into each of the three categories. As a result, we specified the notional system to contain 400 devices, and that 35 percent, 40 percent, and 25 percent of the 400 would respectively be classified into the low, medium, and high cost categories. We used 21 hours mean time between failure (MTBF) as the overall reliability baseline of the avionics system model.

A note on terminology: We assume here that every reported failure in our baseline examples (without redundancy) results in a demand for a part. Thus, we use the phrase "mean time between failure (MTBF)" interchangeably with "mean time between demand." We also use "mean time between critical failure (MTBCF)" to designate the time between failure of essential mission functions. In a redundant system, one might have a failure of one component that is not a critical failure, since a redundant component can perform its function.

Modeling the avionics system using Dyna-METRIC required information not available at this stage in the acquisition process. Specifically, we required (1) the percentage of devices falling into the three reliability categories; (2) the distribution of devices over the 3-by-3 matrix of cost-reliability categories; and (3) the reliability levels associated with each of the three categories. In order to provide a basis for estimating these data we adopted the F-15C as a baseline model.

The first step was to analyze the distribution of the F-15C's avionics device unit costs and failure rates. The data for this analysis were the F-15C SRU and LRU databases used by AFLC for the development of WRSKs. The distribution of costs and failure rates were similar in shape, whether based on SRUs or LRUs. The distributions were skewed toward the low-cost/low-failure rate (high reliability) end with relatively long tails on the high-cost/high-failure rate (low reliability) end. We thus chose to adopt the same 35/40/25 percent division of devices into high, medium, and low categories for failure rates as we adopted for unit costs.

Only 16 percent of the SRUs are more expensive than the mean cost and only 18 percent of the SRUs have a demand rate greater than the mean demand rate. Only 4 percent of the costs are greater than the first standard deviation beyond the mean. Only 6 percent of the SRUs have a demand rate greater than 1 standard deviation beyond the mean demand rate. Meanwhile, the median cost is .24 standard deviation less than the mean and the median demand rate is .29 standard deviation less than the mean. Finally, the 5 percent most expensive SRUs lie between the .85 and 10.66 standard deviation, while the SRUs with the 5 percent greatest demand rates lies between the 1.3 and the 9.39 standard deviation.

We adopted the F-15C SRU data base of 464 SRUs as the basis for classifying devices into unit cost-reliability categories. Specifically, we assumed that high cost items would be over-represented in the high-failure-rate category (low reliability) relative to the frequencies expected under independence and would be under-represented in the low-failure-rate category. Conversely, we assumed that low-cost items would be over-represented in the low-failure-rate category and under-represented in the high-failure-rate category relative to the frequencies expected under independence.

The F-15C data base exhibited these properties. If cost and failure rate were independently distributed among the LRUs we would expect 6.25 percent of the devices to fall in the high-cost/high-failure-rate category (.25x.25) and 8.75 percent (.35x.25) of the devices to fall in the high-cost/low-failure-rate category. However, we observed 12.1 percent and 2.8 percent of the devices to fall into the respective categories. We also observed a similar but opposite pattern for low-cost devices (12.25 percent and 8.75 percent expected under independence, respectively, for the low- and high-failure-rate cells versus corresponding observations of 17.9 percent and 5 percent).

Table VI-1 displays the percentage of devices falling into each of the nine cost-by-failure rate categories. Percentages in parentheses are the respective percentages expected on basis of independence between cost and failure-rate classification.

For failure rates, we had less explicit information. While the goal for avionics system MTBF was available, there was no indication of how this goal was associated with

MTBFs of individual modules. The approach we took to developing failure rates to be associated with the three reliability categories involved two steps. First, we determined median failure rates for the three reliability categories developed from the F-15C SRU data base. Next, we adjusted these failure rates to values that would yield an overall reliability of 21 hours for the subject system.

In converting the overall reliability goal into module MTBFs, we initially assumed no redundancy. In a baseline database with no redundant devices, Dyna-METRIC represents the equipment as though it were organized in a serial design. Thus, the failure of any piece of equipment makes the subject system not fully mission capable.

Table VI-1. Percentage of F-15C SRUs Falling into Cost-Failure Rate Categories

	Failure Rates			
Cost Category	Low	Medium	High	Total
Low	17.9%	12.1%	5.0%	35%
	(12.25)	(14.0)	(8.75)	
Medium	14.2%	17.9%	8.0%	40%
	(14.0)	(16.0)	(10.0)	
High	2.8%	10.1%	12.1%	25%
	(8.75)	(10.0)	(6.25)	
Total	35%	40%	25%	100%

Note: Figures in parentheses are expected cell percentages assuming that cost and failure rate are distributed independently.

Thus, we can calculate an overall failure rate for a system modeled in Dyna-METRIC by summing the failure rates of all the equipment being modeled. The overall reliability is calculated by taking the reciprocal of this sum. Thus, a system reliability of 21 hours, our ATF baseline, is equivalent to an aggregate failure rate of about 4,762 failures per hundred thousand flying hours (1/21 x 100,000).

We first calculated an initial aggregate failure rate for the system to be modeled. This is done by dividing the assumed number of equipment (400) into the three reliability categories discussed above (35/40/25percent split) and multiplying these frequencies by the median failure rates obtained from the corresponding F-15C data base categories.

We then adjusted these median failure rates by multiplying them by the factor (target aggregate failure rate/initial aggregate failure rate). In the case of a target reliability of 21 hours, an initial aggregate failure rate of 9,524 failures per hundred thousand flying hours developed from the data implies a reliability of 10.5 hours. Uniformly scaling the three initial category failure rates down by a factor of .5 produces category failure rates consistent with an aggregate reliability target of 21 hours.

Moving from the F-15C data base of 464 pieces of equipment to that of the modeled system containing 400 pieces required another adjustment. The adjustment from initial to target reliability was correct for a system also containing 464 pieces of equipment divided identically among the three failure-rate categories. In order to correct for differences in amount of equipment we again multiplicatively scaled the failure rates uniformly over the three failure-rate categories. Reducing the equipment by 14% from 464 to 400 would also reduce the aggregate failure rate (and correspondingly increase the aggregage reliability) within Dyna-METRIC by 14%. Thus, the multiplicative scaling factor to be applied to the three failure-rate categories is 464/400, or 1.16.

The joint distribution of failure rates and unit costs over the nine failure rate-by-unit cost categories observed in this data base gave us a model upon which to base the distribution for the modeled aircraft. Finally, the failure rates observed in the F-15C SRU WRSK data base provided us with a starting point from which we scaled the failure rates to a level consistent with information provided to us about the target reliability for the modeled system. These values are given in Table VI-2.

Table VI-2. Assumed Joint Distribution of ATF Avionics Costs and Demand Rates

Module	Demand Rates per 100,000 Flying Hours		
Costs	3.3	8.3	29.8
$7,000	18%	12%	5%
$14,000	14%	18%	8%
$23,000	3%	10%	12%

In order to address uncertainties about the data base, we analyzed excursions from this baseline by varying the overall level of reliability, unit cost, and equipment redundancy over three levels each within a three-by-three factorial design. We varied overall target reliability over three levels—the ATF baseline of 21 hours and lower levels of 10.5 hours and 5.25 hours. These changes to the baseline are reflected by proportional changes in the failure rates associated with the three failure-rate categories (i.e., halving overall reliability requires doubling the component failure rates).

We varied overall unit costs over three levels, the baseline level and two increased cost levels. Recall that unit costs in the baseline condition were taken as $7,000, $14,000, and $23,000 for the low, medium, and high cost categories. In the first increased cost condition, we increased the value of the medium cost category to $21,000 and that of the high cost category to $46,000. In the second increased cost condition, we increased the value of the medium cost category to $28,000 and of the high cost category to $46,000.

Redundancy was simulated by assuming that the initial candidates for redundancy were those that failed frequently but were low cost. We modeled three levels of redundancy—no redundancy, low redundancy (5 redundant devices out of 400), and high redundancy (20 redundant devices out of 400).

C. RESULTS

1. Cost of Avionics WRSKs Under Varying Reliability Levels

Table VI-3 displays the sparing cost requirements evaluated by Dyna-METRIC (1985 dollars) for the three reliability levels under baseline conditions, without redundancy. Because it has been suggested that the flying program for the ATF is more challenging than that for the F-15C, we calculated cost assuming that the system would meet the goals of the moderate surge flying program. (75 sorties per day for days 1-6 and 49 sorties per day thereafter through day 30).

Table VI-3. Cost of WRSKs for Simulated ATF Avionics Suite, Moderate Surge Flying Program (Thousands of 1985 Dollars)

Level of Reliability	Spares Cost	Cost per Sortie
21 hrs	$1,255	$0.761
10.5 hours	$5,384	$3.265
5.25 hours	$16,040	$9.727

In our ATF avionics simulations, sparing costs vary nonlinearly with reliability level. Halving reliability from 21 to 10.5 hours results in spares costs four times as great.

Halving reliability from 10.5 hours to 5.25 hours results in spares costs almost three times as great.

The variations in sparing costs as a function of reliability were more nearly linear in our study of the F-15C (see Table III-1). In that analysis, halving reliability increased sparing costs by a factor of only 2.3. Reducing reliability by an additional 50 percent increased sparing costs by 53 percent.

We caution that these cost levels are illustrative only. In particular, some very high cost devices are excluded. The "high cost" excursions presented later may be a closer representation of the ATF.

In addition, the sparing costs reported here are low relative to those observed in the study of the F-15C. We believe that these differences are due to the large improvement in aggregate failure rates between the total F-15C (which includes mostly avionics devices, some airframe devices, and a few engine-related components) and the simulated ATF avionics. The "high reliability" F-15C studied in the previous work had an aggregate demand rate of .84 per hour, which corresponds to a Dyna-METRIC reliability of 1.19 hours. By contrast, the summed demand rates implied by the MTBF used in the present study ranged from 0.05 on the high-reliability end (21 hours) to 0.19 failures per hour on the low-reliability end (5.25 hours). This perspective makes the two sets of statistics appear more nearly comparable. Further, a nonlinear relationship between reliability and sparing cost may make the relationship observed in different reliability regimes appear very different, accounting for near linearity in the F-15C study and an approximately exponential relationship in the present study. However, this is only a hypothesis at present.

One additional kind of difference that may contribute to differences in results is the difference in the joint distribution of unit cost and failure rates used in the two studies. The aggregate failure rates may appear comparable but differences in the details of the failure rate distributions may magnify (or mitigate) differences in simulation results. Dependence of cost on failure rate might magnify that difference.

Sparing costs per sortie vary accordingly. If the 21-hour reliability can be achieved, the cost of an avionics WRSK would be less than $1,000 per sortie.

2. Cost of Avionics WRSKs Under Differing Redundancy Conditions

We anticipate the following relationship between system reliability and the value of redundancy relative to sparing costs in a given scenario. Redundant components will have no functional value when either reliability is very great in a suitably "short" scenario or reliability is very poor. Consider the extreme examples of each case. If a component never fails then a redundant component will never be used. For a component with a reliability that is high relative to the operating demands made on it (e.g., a radar isn't used much in a scenario requiring only stealthy operation of the system), the redundant component will only infrequently be required. At the other extreme, if a component fails instantaneously, then redundant parts are also consumed instantaneously and add nothing to the system's performance. Analogously, a component's reliability may be so low relative to the demands made on it in a given scenario (e.g., a scenario requiring extended use of radar or jamming equipment) that redundant parts are consumed quickly, adding little to the performance of the larger system.

Table VI-4 displays WRSK costs for excursions in which reliability is jointly varied with redundancy level, while still maintaining baseline module costs. The displayed sparing costs are adjusted in the redundancy conditions for the costs of acquiring the redundant devices. This cost is $840,000 in the low redundancy condition and $3,360,000 in the high redundancy condition.

In each case we examined, redundancy resulted in higher costs. At very high levels of reliability, this is to be expected. For devices with very few failures, a very reliable system, we would expect it to cost more to carry the spares on board than to spare to availability, as Dyna-METRIC does. This hypothesis is borne out by the fact that the penalty paid for redundancy is the least at the low-reliability level. With more time and resources, one could begin to zero in on the combinations of cost and MTBF for which redundancy makes sense. This result could then be factored in with other engineering decisions on how to approach system robustness.

Table VI-4. Cost of ATF Avionics WRSKs Under Redundancy (Thousands of 1985 Dollars)

	Redundancy Condition		
Reliability Level	None	Low	High
High MTBCF 21	$1,255	$2,037	$4,383
Medium MTBCF 10.5	$5,384	$6,070	$8,114
Low MTBCF 5.25	$16,040	$16,572	$18,168

Note: WRSK costs are adjusted for acquisition cost of redundant devices.

Thus, further redundancy experiments would be useful as the program develops. While initially we chose the high-failure rate, low-cost items for duplication, other assumptions are possible. One might choose high-failure rate, high-cost items for redundancy, on the grounds that high-cost items are vulnerable to jostling or connection problems and should not be removed often. Large or heavy items would not be good candidates for redundancy, so if one had information about the weight and size of specific devices, this could be incorporated in specifying the population of redundant devices.

3. Increased Module Cost Excursions

Because the avionics of several advanced tactical aircraft (i.e., ATF, ATA/A-12, LH) are still in development, there is a substantial degree of risk in the cost estimates for the modules. Therefore, it makes sense to do sensitivity analysis on the module cost estimates. The Increased Cost I scenario involved increasing the cost of the medium-cost modules by 50 percent and of the high-cost modules by 100 percent. The Increased Cost II scenario involved doubling the cost of both the medium- and the high-cost modules. This resulted in total module acquisition costs that were 62 percent higher in Increased Cost I and 82 percent higher in Increased Cost II.

Table VI-5 displays the results for the complete set of 27 conditions in which reliability, redundancy, and unit cost condition are varied in a 3x3x3 design.

Table VI-5. Cost of ATF Avionics WRSKs (Thousands of 1985 Dollars)

	Redundancy Condition		
	None	Low	High
Baseline Cost			
MTBCF 21	$1,255	$2,037	$4,383
MTBCF 10.5	5,384	6,070	8,114
MTBCF 5.25	16,040	16,572	18,168
Increased Cost I			
MTBCF 21	2,148	2,872	5,182
MTBCF 10.5	9,452	10,131	12,147
MTBCF 5.25	27,488	28,006	29,560
Increased Cost II			
MTBCF 21	2,372	3,096	5,406
MTBCF 10.5	10,138	10,803	12,812
MTBCF 5.25	30,260	30,757	32,304

Considering only the three unit cost conditions, we observed an effect on WRSK sparing costs greater than the difference in total module acquisition costs across the three conditions. Increased Cost I cost 62 percent more to acquire but 71 percent more to spare.

Increased Cost II cost 82 percent more to acquire but 89 percent more to spare. This result is consistent with the understanding that unit cost and reliability are inversely related, i.e., high-unit-cost items disproportionately fall into the low reliability category. Thus, increasing the cost of high-unit-cost items alone will disproportionately increase sparing costs because these items tend to have higher demand rates.

4. Fault Detection and Partitioning Excursions

Accurate fault detection ability and efficient partitioning are two goals that will need to be achieved to make substitution of LRMs for LRUs a viable concept.

Fault detection refers to the aircraft's ability to detect device failures using its own built-in test facilities. Past systems have experienced difficulty with faults that occur on the aircraft but cannot be replicated in the shop. Such faults can result in unnecessary removals or in removals without improved performance. The LH and ATF plans call for extensive built-in test capability, which should minimize false alarms.

Partitioning refers to the economic division of avionics functions among devices relative to spare/repair decisions. Economic criteria dictate that high-cost, high-failure-rate items (items with a high unit cost per failure-free flying hour) should be repaired rather than replaced (spared). Optimal partitioning divides avionics functions among devices in such a way that the total cost of maintaining the aircraft, whether incurred through sparing or repairing, is minimized. Under a design philosophy in which most devices will be spared rather than repaired *a priori*, optimal partitioning divides avionics functions in such a way that the total cost of maintaining the aircraft is minimized for the stated maintenance constraint.

Partitioning is easiest when all items can be designed to have similar failure rates. Items with unusually high failure rates cause problems for the designer. In the case of the LH and ATF avionics, which are planned for two-level repair, items with very high failure rates—bad actors—jeopardize the two-level maintenance concept.

In this research we made preliminary evaluations of the risk to sparing cost should fault detection and parititioning goals not be met. This was done by selectively increasing the demand rate experienced by the modeled devices.

For the case of degraded fault detection, we increased the modeled failure rate of all devices by 30 percent across the three baseline reliability levels. This implied a lower overall reliability for the aircraft. In order to explore the bad actors scenario, we increased the failure rate of half of the high-cost/high-failure-rate items by a factor of 4 across the three baseline reliability levels, then adjusted the failure rates of the rest of the devices to maintain the MTBF levels of 5.25, 10.5, and 21.

Avionics WRSK costs for these excursions are presented in Table VI-6. As expected, these costs are substantially higher than the baseline. The bad actors simulations indicate that, even if the higher reliability level is achieved overall, bad actors can more than triple the cost of the WRSK.

Table VI-6. Avionics WRSK Cost Under Fault Detection Problems and Bad Actors Scenarios (Thousands of 1985 Dollars)

Reliability	Fault Detection Problems	Bad Actors	Baseline
Low	$22,700	$25,930	16,040
Medium	9,206	11,016	5,384
High	2,533	4,360	1,255

5. Analysis of Sortie-Generation Capability Under Wartime Conditions

In future work, we expect to develop estimates of sortie-generation capability under wartime conditions. As with the real F-15, we expect to be able to analyze the impact of maintenance delay, attrition, and battle damage on sortie generation and on spares cost per sortie.

VII. OTHER COSTS AND BENEFITS OF RELIABILITY

Estimating the impact of reliability on the cost of the WRSK is an important analysis, because it tests the ability of the squadron to fly under conditions where traditional support and repair facilities are not available. In the sense that it severely tests the system, the cost results of the WRSK analysis probably capture the most important effects of reliability. Nevertheless, these are not the only benefits to increased reliability. Savings in manpower and equipment are also likely to occur. While we believe that combat-related issues are extremely important, it may also be useful to consider the impact of reliability on costs under peacetime conditions.

As part of this effort, we have begun to consider costs and benefits of reliability other than those shown in avionics WRSKs. Some potential benefits of enhanced reliability, such as reduced manpower costs, are discussed in Section III. Others can be hypothesized. In this section, we discuss two areas in which we believe further research is needed.

A. THE IMPACT OF INCREASED RELIABILITY ON TOTAL O&S COSTS

1. Background

Total O&S costs may be affected by reliability in several ways. In this effort, we begin to model some of these. Unlike our work with Dyna-METRIC, the modeling here focuses on peacetime costs.

The following estimates are based on a total aircraft O&S cost model adapted by IDA from a model developed by Northrop Corporation. The model uses historical data on the following existing aircraft with at least three years of service: A-7D, A-10A, F-4E, F-5E, F-15A, F-15C, F-16A, F-16C, F-111A, and F-111F. We estimated log-linear cost estimating relationships for various categories of O&S cost by aircraft subsystem—engine, airframe, and avionics.

2. Results

In order to demonstrate the capability of the total O&S cost model, we specified a baseline F-15 and two excursions in ranges similar to those represented as goals for the ATF. In the first excursion, the MTBF of all components was doubled. In the second, reliabilities of major parts of the aircraft were varied differentially—the avionics reliability was quadrupled, the airframe reliability was increased by two-thirds, and the engine reliability was increased by a third.

In these initial simulations, only MTBF was varied. Other characteristics of the aircraft were assumed to be identical to the F-15. We made no attempt to specify ATF characteristics completely, although the model inputs could be modified in this way later. We assumed a 24-aircraft squadron with 311 flying hours per authorized aircraft. For the categories of cost that depend on MTBF, we used the cost estimating relationships. For those costs that are assumed to be MTBF-independent, we used the actual F-15 values.

Table VII-1 shows the results of these simulations. For Simulation 1, doubling reliability, the cost of supporting the squadron was $59.323 million, or 26 percent less than the baseline F-15C. This represented a saving of $15.752 million per squadron. For Simulation 2, total costs were $61.156 million, or 23 percent less than the baseline F-15C. Our preliminary assessment is that the results are sensible—the rankings are as expected, and the magnitudes appear reasonable.

This approach is still being developed and refined. The individual cost-estimating relationships and the model as a whole need to undergo further development and testing. Our conclusion is that this approach shows promise as a useful supplement to the more complex modeling of Dyna-METRIC.

B. ACQUISITION COSTS AND BENEFITS OF RELIABILITY

Our work has indicated that the Department of Defense (DoD) could derive large benefits from better reliability and maintainability in its weapon systems. However, the cost of achieving the reliability improvement has not been established. Standard cost-estimating relationships (CERs) examine the cost implications of purchasing greater capability or technical performance, but have not accounted for component or system reliability.

When deciding how much quality to demand in new systems, DoD needs the ability to estimate the cost implications of designing and manufacturing higher quality equipment. Moreover, this information is required at an early stage in the procurement cycle, so that design and manufacturing processes may be influenced by the cost tradeoffs.

Table VII-1. Results of Preliminary Total Operating and Support Cost Estimates Under Varying Reliability

	Millions of 1986 Dollars			
	Actuals	Predicted	Simulation 1	Simulation 2
Personnel (MMH/FH)				
General Support/Inspections	16.306	15.773	13.367	13.209
Airframe	4.181	3.955	2.140	2.511
Engine	1.904	1.389	0.848	1.134
Avionics	4.546	3.508	1.746	0.869
Total	26.937	24.626	18.101	17.723
Aircraft Maintenance Material				
Airframe	2.182	2.081	1.533	1.659
Engine	0.361	0.798	0.405	0.604
Avionics	1.774	1.731	1.132	0.740
Total	4.316	4.610	3.069	3.003
Replenishment Spares				
Airframe	1.460	1.460	0.836	0.967
Engine	12.431	11.203	7.251	9.366
Avionics	2.323	2.338	1.595	1.088
Total	16.214	15.001	9.681	11.420
Depot Maintenance				
Airframe	1.795	1.747	0.959	1.121
Engine	5.109	6.281	5.147	5.787
Avionics	2.028	1.711	1.267	1.002
Total	8.933	9.739	7.373	7.910
MTBF Dependent Totals	56.400	53.976	38.224	40.057
MTBF Independent Items				
POL	9.354	9.354	9.354	9.354
Wing/Base Staff	1.248	1.248	1.248	1.248
Training Ordnance	1.260	1.260	1.260	1.260
Support Equipment Replacement	1.571	1.571	1.571	1.571
Class 4 Modification Kits	2.086	2.086	2.086	2.086
Aircrew	5.580	5.580	5.580	5.580
TOTAL	77.499	75.505	59.323	61.156

Note: Data are for a 24-aircraft squadron of F-15Cs.

One approach that has been taken is to try to measure the cost of reliability improvement programs (Alexander, Reference [7]). This approach has the virtue of dealing with two different reliability levels within the same system. One caveat is the issue of possible selection bias—only those reliability improvement programs with a high cost-benefit ratio are actually implemented.

Alexander reaches two broad conclusions regarding reliability improvements. First, he argues (p. 11) that reliability may be increased by accepting reductions in system performance:

> It is now generally accepted that for given development resources, pushing the state of the art in seeking high operational performance will also result in unreliable systems. One method for increasing reliability, therefore, is to back off on performance requirements to reduce component stress. Reduced performance is a price that can be paid for higher reliability and is symmetrical with development and production costs in its potential effects. New technology can ease these tradeoffs. Technology can loosen constraints, but it does not eliminate the need for assigning priorities and considering tradeoffs.

Second, Alexander argues that higher *production* costs are not a necessary consequence of increased reliability. He states on p. 19:

> The data on the effect of reliability improvement on unit production costs show that, in most cases, production cost changes were zero. Indeed, in one case examined in detail, the F100 engine Component Improvement Program (CIP), the production unit cost changes were negative—the engine became less costly to produce as a result of the CIP changes. For the Navy's F/A-18 fighter aircraft, we estimated [using CERs] a small production cost effect of 1.6-2.6 percent on the basis of greater weight of the aircraft attributed by the developers to reliability. In some cases, possible production cost increases may have been compensated for by cost reductions arising from learning curve effects, or by contractors absorbing additional costs in reduced profits. *Apparently, when reliability is a high-priority design goal—either in a new program or in a post-development reliability improvement program—the bulk of the cost effects are in non-recurring investments rather than in recurring production costs.* [Emphasis added.]

It would be useful to test Alexander's conjecture that the costs of reliability are borne during the development phase rather than during the procurement phase. It would also be useful to examine a broader range of systems than the handful examined by Alexander using his case-study approach.

As part of this effort, a working paper was prepared that proposes a methodology for appending a quality variable to CERs for tactical aircraft [8]. The paper details data and methods for estimating the costs of quality at any or all of the three major phases in the life-cycle of an aircraft: development, procurement, and operations. The emphasis is on tactical aircraft because the cost data are readily available, and because baseline CERs (omitting quality) have already been established. Initial development of this work it is now being pursued as an IDA Central Research Project.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

In this analysis, we discussed methods to measure the considerable benefits of increasing weapon reliability. The principal measures were the cost of the WRSK—under baseline conditions and also taking account of wartime conditions—and sortie generation.

In every case we examined, higher reliability resulted in better performance. Doubling reliability can cut the cost of the WRSK by more than nalf.

Sortie generation is also greater for more reliable aircraft. For instance, we observed in our study of the F-15C that when maintenance delay is introduced into the baseline scenario, the "high reliability" aircraft achieves 14-percent more sorties than the nornal aircraft, along with a 62-percent reduction in spares cost per sortie.

Another issue we wanted to explore was how stressful combat conditions affected the value of reliability. The usual planning factors often do not allow for some conditions that are likely to occur. For example, battle damage places demands on the maintenance system and creates delays and downtime. It was unclear whether reliability might be unimportant when time must be taken to repair battle damage; our analysis indicated that, even with a relatively high level of battle damage, reliability has substantial value. When the most severe combat condition is added to the baseline scenario—one that includes maintenance delay, attrition, and battle damage—higher reliability results in a 33-percent increase in the number of sorties achieved at less than one-third the spares cost per sortie.

Challenging sortie schedules also underscore the value of reliability. When spares are purchased for a normal sortie schedule and then a more challenging flight schedule is attempted, which may occur if a conflict becomes intense, reliability results in substantially more sorties. In the most severe case we examined—a 30-day surge situation with maintenance delay, attrition, and battle damage—the "high-reliability" fighter achieved 358 sorties, while the "normal-reliability" fighter achieved only 233, a 54-percent advantage.

We also began to develop a method for assessing the value of reliability in prospective systems. The IDA method allows for an initial assessment using only the most general information. As the information expands and improves, the method accommodates it.

We demonstrated the method with planning factors for the ATF avionics, a system with both greatly increased inherent reliability and major architectural changes. When reliability improvements can be made without major architecture change, the value of reliability can be assessed relatively easily. Our method can be used for making reliability/cost tradeoffs. Of course, uncertainty about the details of the ATF design implies uncertainty about WRSK costs, but our conclusion is that the IDA models and methods can be adapted to assess the reliability of the most important features of these advanced architectures.

In our ATF avionics simulations, sparing costs vary nonlinearly with reliability level. Halving reliability from 21 to 10.5 hours results in spares costs 4 times as great. Halving reliability from 10.5 hours to 5.25 hours results in spares costs almost 3 times as great.

In each case we examined, redundancy resulted in higher costs. At very high levels of reliability, this is to be expected. For devices with very few failures, a very reliable system, we would expect it to cost more to carry the spares on board than to spare to availability. This is consistent with the current planning for ATF, which includes only a small amount of redundancy. With this method, one could assess the combinations of cost and MTBF for which redundancy makes sense.

We examined cost options in which some very high cost devices are assumed. We found that increasing the cost of the high-unit-cost items alone will disproportionately increase sparing costs because these items tend to have higher demand rates. We also examined a situation in which there are some devices with very high failure rates. We found that, even if high reliability is achieved overall, the presence of a few unreliable parts (e.g., poor partitioning) can more than triple the cost of the WRSK.

If the avionics for the advanced tactical fighter meets its cost and reliability goals (admittedly a big if), WRSK sparing costs appear to be minimal. This raises the issue of repair policy and repair infrastructure. Does it make sense to maintain a repair infrastructure for items which seldom fail?

We have developed a framework for the new system reliability assessment method. This analysis can indicate the benefits of additional reliability, but it does not reflect all the costs or all the cost savings of additional reliability. Examining the cost dimension in more detail is essential, because cost must be balanced against the corresponding benefits.

B. RECOMMENDATIONS

The new avionics architectures must be evaluated using appropriate techniques. While these new architectures offer potential for significant support cost savings, they also present considerable difficulties in analysis. However, if these new architectures are not sufficiently analyzed, their potential benefits and costs may not be adequately recognized during the acquisition process. The analyses should address as much of life-cycle cost as possible, as well as the availability implications of alternative configurations.

Combat conditions—maintenance delay, battle damage, and attrition—substantially affect a squadron's ability to fly sorties. We believe that the services should more closely consider combat conditions when determining which parts are mission essential and in building spares kits. The goal should at least be to spare as you would expect to fight. Perhaps it should be to spare as you fear you may have to fight. Sparing methodologies that assume instantaneous repair and no battle damage should be revised.

The services should consider instituting more reliability improvement programs for tactical aircraft. Spares cost savings aside, reliability has substantial payoff in combat.

It is important that OSD assess the reliability of new systems early in the acquisition process. At a time when resources are constrained, it is extremely important to be able to consider the entire life cycle of a weapon system early in the process, when little information is available. This is particularly important when considering questions of operating and support, which frequently are overlooked in the more immmediate concerns about technology development. The new system reliability assessment method illustrated here is potentially useful for this purpose.

We recommend continuing to analyze the ATF as better data become available and as planning factors change. As a first approximation, we have worked with generic devices. More complete information on the reliability of particular functions is likely to become available. The method has the capability to vary reliability differentially within the aircraft.

Design teams need to assess cost-reliability tradeoffs in their trade studies. The new system reliability assessment method illustrated here could be used in combination with estimates of the investment cost of a repair network to guide maintenance policy.

The method can also be used by the government to do sensitivity analysis of the impact of not meeting goals in such areas as reliability, cost, and fault isolation, as we demonstrated with our example ATF avionics suite. It can also incorporate information about commonality of devices. It should be used for those purposes.

A more complete analysis of the ATF would also include consideration of the operating plan for the ATF, including higher sortie goals and operation and maintenance from diverse locations; consideration of improved time to repair as a result of easier access to line-replaceable modules (LRMs) and faster fault isolation; and consideration of costs of manpower and support equipment.

Additional research to support continued development and experience with the method of assessing new systems should be performed. For example, analyses of additional systems are needed to examine whether different distributions should be used to develop simulated data for different kinds of systems. An important additional excursion that needs to be evaluated is to vary maintenance concept between two-level and three-level maintenance.

In addition, some housekeeping details need to be taken care of to maintain the new system reliability assessment method. We have recently received an updated database for the WRSK parts for the F-15C and the F-15E. Our model should be updated to reflect this. Computing capabilities for the method need to be kept up to date. It would be particularly useful to have a PC-based method for generating Dyna-METRIC data sets or a PC version of Dyna-METRIC.

We recommend expanding the method to cover other types of systems. Missiles appear to be the best candidate for an expansion. Ideally, a library of databases for analogous systems would be maintained.

We recommend continuing the analysis of O&S cost models with broader coverage as a supplement to the Dyna-METRIC model. We also recommend establishing a method of adding the cost of increasing reliability into the analysis.

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REFERENCES

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APPENDIX A.

THE DYNA-METRIC MODEL'S CAPABILITIES, OUTPUT, AND LIMITATIONS

APPENDIX A.

THE DYNA-METRIC MODEL'S CAPABILITIES, OUTPUT, AND LIMITATIONS

This appendix describes the Dyna-METRIC model's capabilities, which include assessing systems performance in a dynamic wartime scenario and assisting in identifying factors that may limit operational performance. Some of the model limitations are also discussed. (The reader seeking additional detail is referred to References [A-1 through A-3].)

Dyna-METRIC was selected as the primary model to use in studying the effect of aircraft repairable spares on warfighting capability. The model provides a representation for predicting fully mission capable (FMC) status of a complete squadron of Air Force aircraft. The model accepts a flying-hour program for scenarios up to several months in length. Output from the model includes expected sortie generation capability along with a listing of potential problem parts for Remove, Replace and Repair (RRR) and Remove and Replace (RR) maintenance items.

One major reason for selecting the Dyna-METRIC model for use in the IDA study is that Dyna-METRIC is used by the Air Force to determine the components and repair parts to stock in WRSKs and Base Level Self-Sufficiency Spares (BLSS) to support up to 30 days of austere wartime flying. In addition, the Dyna-METRIC model is currently one of the leading models for generating reliability insights for items such as electronic warfare equipment.

The Air Force Logistics Command (AFLC) is using Dyna-METRIC in its Weapon System Management Information System (WSMIS) to assess theater-level supportability of wartime operating plans. WSMIS is being expanded to assess repairable spares and engines for almost all Air Force weapon systems. Dyna-METRIC spares assessments are closely related to the requirements process used to compute Air Force authorizations.

Dyna-METRIC computes an expected pipeline value, which becomes the minimum quantity for each part. A safety level is then added using a marginal analysis procedure until a specified not mission capable status (NMCS) and backorder goal is achieved for the squadron.

WRSK/BLSS computations assume that the failure rates for most parts are functions of flying hours. For non-optimized (NOP) items, such as guns, landing gear, and support equipments, the required quantities for the kits are manually determined based upon expert judgment supported by whatever demand data are available.

Air Force Logistics Assessment Exercises such as Coronet Warrior have indicated a close relationship between Dyna-METRIC model results and actual exercise experiences.

A. CAPABILITIES OF DYNA-METRIC

Dyna-METRIC provides a detailed representation of the logistics system for many individual aircraft components—particularly in the areas of component demand processes such as time, flying hour, and onshore and offshore demand factors, and repair processes such as not repairable this site (NRTS) indicators. Different repair times at different echelons may be considered by the model, along with different repair resources and scope of repair at different echelons. The model can also do depot workload and stockage computations and can compute base-level stockage with a no-cannibalization constraint. (Cannibalization is the practice of transferring a serviceable component from one aircraft to another.) Cannibalization is used only when a serviceable component needed to repair one aircraft cannot be obtained from local supplies and another aircraft is already unserviceable because of failure of other components.

The primary measure of performance for the model is the calculation of the FMC aircraft and sorties generated from the flightline. The Dyna-METRIC model can simulate one or more types of aircraft, at one or more bases located in one or more theaters of operations, for a period of time that may range from several days to several years. The model can predict the effect of the logistics support system on the bases' ability to execute their assigned flying programs.

Aircraft can operate out of a base on a fly-out, fly-back sortie program (as fighter aircraft typically do) or on a fly-in, fly-out program (for example, a cargo aircraft flying a circuit). In either case, broken parts arrive with incoming planes but, in the case of cargo aircraft, removals of failed components may be more likely at some bases than at others.

Although aircraft of a given type are usually assumed to be identical, they can be flown on different missions at different times. For example, a base might fly air-to-air missions for some initial period and subsequently fly ground attack missions. The flying programs to be executed may vary over time. The number of aircraft can increase with the deployment of new units and decrease due to attrition or the reassignment of aircraft. The number and length of sorties may vary each day, as can the maximum single aircraft sortie rate, which limits the number of sorties that can be flown by one operational aircraft in a single day. With this flexibility, the model can accommodate almost any conceivable flying program, including the peacetime or wartime scenarios.

1. Aircraft

Aircraft are assumed to have an indentured component structure: an aircraft is composed of line-replaceable units (LRUs) that are composed of shop-replaceable units (SRUs) that are composed in turn of sub-SRUs. (Sub-SRUs would include both bits and pieces that are consumed during repair of the SRU and other repairable components that may be repaired either locally or at a higher echelon.)

Dyna-METRIC views the entire aircraft as a collection of LRUs, SRUs, and sub-SRUs. Certain major aircraft components, such as engines, are generally not indicated LRU numbers, but they can be treated as LRUs by the model.

In the model, aircraft availability is a direct function of the availability of the aircraft's LRUs. SRUs affect aircraft availability only through their ability to support the repair of their parent LRUs, and sub-SRUs affect aircraft availability through their support of the repair of SRUs.

A given LRU may be on an aircraft one or more times. LRUs can be classified as essential, wholly or partially redundant. If wholly or partially redundant, more than one unit must fail before the aircraft is rendered not fully mission capable (NFMC).

LRUs may also be classified as essential or non-essential to a particular mission that the aircraft can execute. For example, a plane with a broken radar unit might be incapable of executing an air-to-air mission but capable of ground attack.

The model also accommodates the possibility of limited differences in the components on the aircraft location at a single base. This situation may occur when components are being phased in or out or when some of the aircraft are specially equipped.

2. Logistics System

In the Dyna-METRIC model, repairable components essentially move upward in a hierarchical level of repair stations. Repairable parts are removed from aircraft at the flightline, and are serviced at the base level. If not repairable there, they are transported to a Centralized Intermediate Repair Facility (CIRF) and serviced. If not repaired at the CIRF, they are sent on to the depot. Parts at any level can be condemned as not repairable. Stocks of serviceable spare parts may be held at each level, and over time these serviceable spares are sent down the hierarchy to replace the repairable ones that have been sent up.

The repair capabilities of each level can be modeled in considerable detail. Repair for LRUs can be specified as unconstrained or constrained. In the unconstrained case, maintenance is assumed to begin as soon as a component arrives at a repair facility. In the constrained case, the arriving components join a queue of other components also awaiting service. Components are selected from this queue based on a priority scheme that minimizes maximum back orders rather than on a first-come, first-served basis. How long a component waits for service depends on how many aircraft are NFMC relative to other components and on how heavily loaded the repair facility is. In addition to handling repairable items, Dyna-METRIC can handle consumables if these components are assigned a condemnation rate of 100 percent.

Dyna-METRIC portrays the component support processes as a network of pipelines through which components flow as they are repaired or replaced. Each pipeline segment is characterized by a delay time that arriving components must spend in the pipeline before exiting the segment. Some delay times, such as local repair times, vary from component to component; others, such as intratheater transportation times, depend on the base being assessed. There may also be times when components are frozen in their pipeline segments and do not flow. For example, the transportation segments are modeled as being frozen when a transportation cutoff is in effect.

Failed components enter the pipeline network at the bases' flightlines. Each base has a flightline support capability that removes and replaces those components, drawing serviceable spares from local supply as needed to repair aircraft. Each base may also have component repair shops that test the failed components and return them to serviceable condition. For units deploying to new bases, the repair capability may be available only after some delay, while the repair facility is being deployed and set up.

Once components have been removed from an aircraft they are repaired at a local shop or sent to other facilities for repair. If the component can be repaired locally it is returned to local stock. If the component cannot be repaired at all, the base condemns the component and requisitions a replacement.

If the component cannot be repaired at the base, it is declared NRTS and sent to either a CIRF or a depot, and a replacement component is requisitioned. Replacement components are requisitioned from the facility to which the NRTSed component is sent; that facility will immediately send the base a serviceable spare if one is available. If none is available, one will be sent as soon as possible after all prior requisitions for the same component have been filled. Once the repairable component reaches the CIRF or the depot, it is repaired and returned to that facility's stock so that it can be issued to satisfy the next demand.

If a component is sent to a CIRF and the CIRF cannot perform the repair, the CIRF will either condemn the component or send it to the depot, and will requisition a replacement component from the depot. If a component is sent to the depot and the depot cannot perform the repair, the depot condemns the component and orders a replacement from the supplier. (If the scenario does not permit resupply of the depot, the supplier may be cut off.) As LRUs are processed at the various facilities, failed SRUs may be discovered. The SRU repair and resupply network is essentially the same as that for LRUs, as is the repair and resupply network for sub-SRUs.

3. How the Model Represents the Logistics System

The key equation in Dyna-METRIC computes the expected pipeline contents for each LRU, SRU, or sub-SRU. The expected number of each component is calculated for each segment of the pipeline network. The computation is based on the planned time-dependent aircraft flying activity or (optionally) on the achievable partially mission capable (PMC) and FMC time-dependent aircraft flying activity.

The model computes the removals caused by the flight plan activity, and then, using the time-dependent availability and delays associated with transportation and repair at bases, CIRFs, and depots, and the likelihood that the component will be classified as NRTS or condemned, determines the expected contents of each pipeline segment. The segments are totaled to forecast the total pipeline size, which is the expected quantity on order and in local repairs as seen by each base. The expected total pipeline size is the key parameter for a probability distribution that describes the number of components in the network, as seen at each base's flightline. That is, the expected total pipeline size is used to determine the probability that there are two components, the probability that there are three components, and so on.

Dyna-METRIC combines each component's dynamic demand and repair process time to estimate the expected pipeline quantity for each pipeline segment. The dynamic demands for pipeline segments after the base repair pipeline segment are derived from the dynamic departures from the preceding pipeline segment. For example, the LRUs entering the base-to-CIRF pipeline are just the NRTS rate times the departures from the base repair pipeline segment.

The model computes expected pipeline quantities for each LRU's, SRU's, and sub-SRU's repair pipeline segments at base, CIRF, and depot and transportation segments between these locations. SRUs awaiting parts at each location are computed for the number of sub-SRUs in stock and under repair, and LRUs awaiting parts are computed from SRUs in stock, in repair, and awaiting parts.

Backorders at depots and CIRFs are computed from quantities in stock, quantities in repair, quantities of awaiting parts, and on-order. Those backorders are allocated to bases under a first-come, first-served rule. The expected base pipeline for LRUs, SRUs, and sub-SRUs then consist of items in local repair and on order from higher echelons (i.e., in transit and backorder).

B. OUTPUTS OF THE MODEL

Given a description of a scenario, the profile of the aircraft, and the logistics system, Dyna-METRIC provides various measures of performance. Besides traditional component-oriented logistics statistics such as backorders, Dyna-METRIC provides higher combat capability-oriented measures related to the force's ability to generate sorties. The combat measures include aircraft availability and daily sortie generation capability. For each operating location the model reports the expected number of available aircraft at any specified time and at any specified confidence level. For example, Dyna-METRIC might report that on day 5 of a scenario, a given base could expect, on average, 16 available aircraft, but that only 13 aircraft will be available with 95-percent confidence.

Dyna-METRIC also estimates the expected number of sorties a base can generate on any specified day. The model assumes that a base never overflies the program specified in the scenario (though the base may fail to achieve its program due to a shortage of available aircraft), so the predicted sortie generation capability will be less than or equal to the scenario's flying program. Thus, the model's daily sortie estimates reflect both requested sorties and available aircraft.

Higher-order performance measures are quite sensitive to whether or not LRUs can be cannibalized from one aircraft to repair another. Aircraft availability and sortie generation are typically much higher under a full cannibalization policy than under one of no cannibalization. The model allows the user to label each LRU as cannibalizable or not cannibalizable, and then computes aircraft availability and sortie generation first using this data, then assuming a policy of full cannibalization. A policy that permits no cannibalization can be modeled by marking all components not cannibalizable.

From the expected base pipeline value, the model derives the probability that a given number of components are in repair or on order at each base. Using these total pipeline probability distributions for each component and the component's available stock at each base, the model next forecasts how the LRUs in repair and on order would (probabilistically) generate backorders (or aircraft "holes") for each component at a given time. It then distributes those holes across aircraft for two alternative cannibalization policies. For full cannibalization, Dyna-METRIC assumes that all component holes at each base are instantly consolidated on the fewest possible aircraft, thus making as many FMC aircraft as possible.

For partial cannibalization, holes of LRUs flagged as not cannibalizable are assumed to occur randomly across the aircraft at each base. Holes of cannibalizable LRUs are then consolidated onto the aircraft that are already down for noncannibalizable LRUs. Leftover holes are consolidated onto as few of the remaining aircraft as possible. In each case the model derives a full probability distribution for the number of degraded aircraft from which the fields in the capability assessment report are directly obtained. In particular, the expected number of NFMC aircraft and the expected number of FMC sorties are computed and reported for both cannibalization policies.

Dyna-METRIC generates a report that identifies the LRUs that are most likely to be a problem for at least one base, and sorts them by the number of aircraft they are likely to ground. This report is especially helpful when the projected performance is unsatisfactory. For these LRUs, the model reports:

- How many aircraft they will probably ground

- How many aircraft they would ground if the base level spares were most effectively redistributed
- Where in the logistics system the LRUs are tied up (such as, queued for repair at the CIRF, in transit from the depot, awaiting serviceable SRUs at a base.)
- Which SRUs (and sub-SRUs) are tied up and where, if they limit LRU availability.

Two requirement computations are incorporated in the model. The stockage algorithm optionally computes stock with simple, single component fill rate goals or with full- or no-cannibalization FMC aircraft goals. The depot workload requirement computes the maximum and minimum workload necessary for a depot surge to meet its expected requisition levels for each component.

The pipeline probability distributions are used to compute stockage requirements. For this option, Dyna-METRIC recommends additional LRU, SRU, and sub-SRU stock to achieve an NFMC goal at the lowest cost. Two general strategies are employed: buying spares to ensure that each component will individually achieve a target NFMC limit (disregarding other components) and buying spares so that all LRUs jointly achieve the NFMC limit. Note that the first strategy does not achieve the goal of the second. Suppose that there are two LRUs, and each has a 0.1 probability of causing too many NFMC aircraft, so there is sufficient stock of each under the first strategy. But the probability that at least one of the two components will cause many NFMC aircraft is 0.19, so additional stock must be purchased to achieve the more ultimate aircraft-oriented goal under the second strategy.

If the user's objective is only to ensure that each LRU does not violate the NFMC limit with the stated confidence level, the model uses the LRU's individual pipeline probability distributions and increases each LRU's stock level until the stated confidence level is achieved for that component alone. If the objective is to ensure that all of the LRUs jointly achieve either a certain confidence of fewer than the stated percent NFMC, with full cannibalization, or expected NFMC less than a target NFMC percent with no cannibalization, the model first makes sure that each LRU achieves the goal individually, it "buys" more LRUs across the full range of LRUs to achieve the overall goal. In either case the model employs a marginal analysis technique. It first determines how much closer to the goal the user would be with an additional unit of LRU 1, LRU 2, or LRU 3, and so on. It then adds an additional unit of the LRU with the best benefit to cost ratio and it continues to add LRUs in this manner until the goal is attained.

A final Dyna-METRIC option is computing the maximum possible wartime depot repair workload (the expected daily arrivals for depot repair), the minimum required wartime depot workload (the minimum number of LRUs that must be inducted on each day into depot repair to satisfy expected depot requisitions), and the amount of LRU stock needed at the depot to offset repair and retrograde transportation delays under dynamic wartime conditions.

C. LIMITATIONS

Dyna-METRIC has several limitations that arise from the model's mathematical assumptions, approximations, and program implementation constraints. Generally, the mathematical assumptions exist because of the current state of the art in the modeling of inventory systems. Overcoming these limitations will require new mathematical breakthroughs. Using mathemetical approximations reflects design choices that trade off mathematical rigor against extra computer time.

Dyna-METRIC's eight most frequently noted limitations are tied to mathematical assumptions, approximation, or implementation constraints:

- Unconstrained repair may overestimate or underestimate performance. In the model's simplest uses where constrained repair is not modeled, the mathematics underlying the model make two key assumptions about demands, transportation, and repair processes. First, demands arrive randomly according to one of two well-known arrival probability distributions (Poisson or negative binominal), and second, repair and transportation times have known probability distributions that are independent of the demand history. Neither of these assumptions is likely to be exactly true. Thus, these two assumptions may cause the model either to underestimate or overestimate the logistics system performance if repair resources are not explicitly modeled. If one can judge that the demand and repair processes do not deviate radically from these assumptions, the model should be relatively accurate.
- Lateral resupply is not modeled explicitly. The assumption that demands, repair, and resupply functions are independent also prevents the model from directly assessing the effects of lateral supply across bases. Essentially, lateral supply would have the same effect as expedited resupply from a higher echelon. Because the effective resupply time would depend on the history of prior demands, repairs, and resupplied items, lateral resupply violates the model's underlying mathematical assumptions. An approximate workaround exists for this situation, however. If CIRFs are not being used for any other purpose in an analysis, one can model several related bases as being supported

by a CIRF. Some of the theater's stock can then be relocated to the CIRF to be requisitioned and shared across all the bases to simulate lateral resupply.

- The model assumes that aircraft deployed at each base are nearly identical. It does allow for some fraction of the base's aircraft to have additional LRUs, but it assumes that aircraft can be described as subsets of other aircraft. The assumption is critical to the computation of both the full cannibalization and the partial cannibalization of FMC aircraft. Again, a workaround exists if the CIRF feature is not being used in the analysis. One can represent each real base with multiple aircraft types as several bases with a common CIRF containing the base's stocks for all the aircraft. By setting the base-to-CIRF and CIRF-to-base transportation times to zero, one can assess how both unique and common components' support affects the capabilities of multiple aircraft types.

- The constrained repair computations are only approximate. The model uses a deterministic, expected value computation to compute the expected pipelines for constrained, priority repair, so it only approximates real world repair processes. Further, it applies the resulting component pipeline distributions as though they were independent. Thus, the constrained repair computations only approximate likely logistics system performance, particularly when using the model to assess peacetime queueing. Scenario idiosyncrasies may cause some components' backorders to grow until they nearly match the worst component. Then, the model would not consider the correlations induced by priority repair, and it would provide an overly pessimistic assessment of performance. In such a case, one can use the model's problem LRUs report to detect an overly pessimistic assessment. If two or more LRUs that share a repair resource rank near each other in their NFMC impact, the assessment may be somewhat pessimistic.

- Ordering policies for economic order quanities (EOQ) and consumables are not modeled. Some spare parts are so small or inexpensive that they are ordered in economic order quantities greater than one at a time (to avoid the trouble and cost of excess paperwork and handling). The model's mathematics apply precisely only to those cases where the order quantity is one. The mathematics are only approximately accurate for larger order quantity policies. As the order quantity increases, the pipeline variability would also effectively increase. One can work around this approximately by increasing the demand variance-to-mean ratio proportional to the square root of the order quantity. The pipeline variability will then reflect the expected variability due to the order quantity.

- Expected backorders and awaiting parts quantities approximate additive pipelines. For computational efficiency, the model does not compute the joint probabilistic effects of backorders and awaiting parts quantities with related pipelines. Instead, the expected values of these quantities are added to the appropriate pipelines as though they were also Poisson or negative binomial distributions. This is not strictly correct. To treat this rigorously, the model must convolve the related probability distributions—a task that would greatly increase computer time. However, tests of the approximation show that only modest errors are introduced in the computations of total base component breakdowns or NFMC aircraft when the expected back orders or awaiting parts quantities are small (less then 1). When these quantities increase, the errors appear to decrease.

- Flightline and operational constraints are not explicitly modeled. Operational constraints and flightline resources affect the sortie rates that can be achieved with an FMC aircraft. These factors are beyond the scope of the Dyna-METRIC model, so they do not appear explicitly. Nevertheless, their effects can be estimated in other models or analyses and incorporated in the Dyna-METRIC model sortie rate parameter.
- Computers have limitations such as word size representation that may affect the model's precision and accuracy. Unlike the mathematics upon which it is based, the computerized model cannot always carry out its computations with infinite precision. Computer and programming language manuals generally provide maximum and minimum quantities that can be represented. A program like Dyna-METRIC computes extremely small probabilities and adds them up in various ways. Often, a computed probability will be smaller than the programming technique used can represent. Summing these small numbers, or almost zeroes, leads to cumulative errors called numeric instabilities, which may affect the model's results. Dyna-METRIC partially compensates for this effect when possible by using logarithms, which permit the model to represent much smaller numbers. In general, Dyna-METRIC encounters numerical instabilities only in rare cases when the expected pipeline sizes grow extremely large, beyond several thousand units (depending on the computer). Such an instability will result in an extraordinary value for the number of NFMC aircraft—nearly all aircraft will be NFMC. When one encounters such a situation, the problem LRUs report will indicate that one or more LRUs (or SRUs) have very large pipelines. Removing the offending component from the analysis will usually correct the problem. Such components are usually analyzed more appropriately outside the rigorous confines of a model like Dyna-METRIC.

Most of these limitations do not affect the current analysis. Despite any known limitations, Dyna-METRIC is a useful model for the type of analysis IDA is performing. The model allows analysis of a variety of operating tempos and logistic support scenarios at a reasonable level of detail and reasonable computer cost.

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[A-3] Issacson, K. E., C. Tsai, P. Boren, and R. Pyles. *Dyna-METRIC Version 4: Modelling Worldwide Logistics Support to Aircraft Components.* WD-2659-AF, The RAND Corporation, June 1985.

APPENDIX B.

LISTING OF F-15C PACIFIC AIR FORCE LINE-REPLACEABLE UNITS USED IN THE ANALYSIS

APPENDIX B.

LISTING OF F-15C PACIFIC AIR FORCE LINE-REPLACEABLE UNITS USED IN THE ANALYSIS

Table B-1 is a listing of component-related data from the input data set. Column 1 lists the component part name; column 2 identifies the type of component along with the assigned input number. L indicates an LRU component, S indicates an SRU component, and SS indicates a sub-SRU component. Column 3 specifies whether CIRF repair facilities are available for that component. Column 4 specifies when to decide to classify a component as NRTS or condemn the part, either before or after testing. Column 5 is the cost of buying an additional unit of stock of the component. Column 6 specifies the onshore and offshore bases' peacetime demand rate per flying hour. Column 7 specifies the level of repair, where BASE indicates that the component can be repaired at a base, CIRF indicates that the component can be repaired at CIRF, and DEPOT indicates the component can be repaired at depot. Column 8 specifies the peacetime and wartime resupply time, in days of the expected time for the highest echelon that repairs the component to procure a replacement during either peacetime or wartime.

Table B-1. Detailed LRU Information for F-15C PACAF

PART NAME	NUMBER	CAN TEST AT CIRF?	NRTS OR CONDEMN	COST	DEMANDS PER FLYING HOUR ONSHORE	DEMANDS PER FLYING HOUR OFFSHORE	LEVEL OF REPAIR	RESUPPLY (DAYS) PEACE	RESUPPLY (DAYS) WAR
1005000566753	L 1	NO	AFTER TEST	29940.	0.00060	0.00060	BASE	16.0	30.0
1270010405948	L 2	NO	AFTER TEST	50369.	0.00820	0.00820	BASE	14.0	30.0
1270010469884	L 3	NO	AFTER TEST	64321.	0.00680	0.00680	BASE	14.0	30.0
1270010635567	L 4	NO	AFTER TEST	124585.	0.00730	0.00730	BASE	14.0	30.0
1270011838987	L 5	NO	AFTER TEST	77474.	0.01050	0.01050	BASE	14.0	30.0
1280010423952	L 6	NO	AFTER TEST	37610.	0.01120	0.01120	BASE	14.0	30.0
1560010037178FX	L 7	NO	AFTER TEST	78621.	0.00110	0.00110	BASE	25.0	30.0
1650003337185	L 8	NO	AFTER TEST	3340.	0.00140	0.00140	BASE	11.0	30.0
1650010503491	L 9	NO	AFTER TEST	42364.	0.00070	0.00070	BASE	14.0	30.0
1650010653500FS	L 10	NO	AFTER TEST	3654.	0.00080	0.00080	BASE	14.0	30.0
1680010325251	L 11	NO	AFTER TEST	19667.	0.00150	0.00150	BASE	14.0	30.0
1680010473179FX	L 12	NO	AFTER TEST	17360.	0.00170	0.00170	BASE	14.0	30.0
5821001387991	L 13	NO	AFTER TEST	4729.	0.00590	0.00590	BASE	16.0	30.0
5821011365467	L 14	NO	AFTER TEST	5741.	0.00420	0.00420	BASE	16.0	30.0
5821011369512	L 15	NO	AFTER TEST	5044.	0.00590	0.00590	BASE	16.0	30.0
5826002625018	L 16	NO	AFTER TEST	9318.	0.00070	0.00070	BASE	8.0	30.0
5826010121938	L 17	NO	AFTER TEST	1865.	0.00520	0.00520	BASE	19.0	30.0
5826010211744	L 18	NO	AFTER TEST	8240.	0.00140	0.00140	BASE	14.0	30.0
5836010512886CX	L 19	NO	AFTER TEST	2586.	0.04050	0.04050	BASE	16.0	30.0
5841010032850	L 20	NO	AFTER TEST	67308.	0.00500	0.00500	BASE	14.0	30.0
5841010486312	L 21	NO	AFTER TEST	102078.	0.00640	0.00640	BASE	14.0	30.0
5841010588862	L 22	NO	AFTER TEST	12465.	0.00050	0.00050	BASE	14.0	30.0
5841010603721	L 23	NO	AFTER TEST	277457.	0.00750	0.00750	BASE	14.0	30.0
5841010630855	L 24	NO	AFTER TEST	340306.	0.01040	0.01040	BASE	14.0	30.0
5841011007363	L 25	NO	AFTER TEST	397056.	0.01430	0.01430	BASE	14.0	30.0
5841011234126	L 26	NO	AFTER TEST	151639.	0.00430	0.00430	BASE	14.0	30.0
5841011331822	L 27	NO	AFTER TEST	394321.	0.00760	0.00760	BASE	14.0	30.0
5841011356194	L 28	NO	AFTER TEST	239604.	0.01120	0.01120	BASE	14.0	30.0
5841011582818	L 29	NO	AFTER TEST	403587.	0.00620	0.00620	BASE	14.0	30.0
5865004775704EW	L 30	NO	AFTER TEST	2122.	0.00090	0.00090	BASE	17.0	30.0
5865010131798EW	L 31	NO	AFTER TEST	1632.	0.00010	0.00010	BASE	16.0	30.0
5865010456276EW	L 32	NO	AFTER TEST	93682.	0.03630	0.03630	BASE	19.0	30.0
5865010548810EW	L 33	NO	AFTER TEST	32349.	0.00580	0.00580	BASE	20.0	30.0
5865010668075EW	L 34	NO	AFTER TEST	91545.	0.03900	0.03900	BASE	11.0	30.0
5865010891745EW	L 35	NO	AFTER TEST	22566.	0.00200	0.00200	BASE	14.0	30.0
5865010891808EW	L 36	NO	AFTER TEST	77072.	0.00790	0.00790	BASE	13.0	30.0
5865011003768EW	L 37	NO	AFTER TEST	59193.	0.01820	0.01820	BASE	12.0	30.0
5865011003769EW	L 38	NO	AFTER TEST	7061.	0.00070	0.00070	BASE	21.0	30.0
5865011003770EW	L 39	NO	AFTER TEST	80985.	0.02550	0.02550	BASE	13.0	30.0
5865011003771EW	L 40	NO	AFTER TEST	7036.	0.00200	0.00200	BASE	30.0	30.0
5865011003830EW	L 41	NO	AFTER TEST	18725.	0.00080	0.00080	BASE	9.0	30.0
5865011142469EW	L 42	NO	AFTER TEST	16053.	0.00140	0.00140	BASE	14.0	30.0
5865011360443EW	L 43	NO	AFTER TEST	43247.	0.04970	0.04970	BASE	11.0	30.0
5865011449320EW	L 44	NO	AFTER TEST	160776.	0.01110	0.01110	BASE	10.0	30.0
5865012112335EW	L 45	NO	AFTER TEST	43247.	0.04470	0.04470	BASE	14.0	30.0
5895003278781	L 46	NO	AFTER TEST	2814.	0.00210	0.00210	BASE	11.0	30.0
5895003409619	L 47	NO	AFTER TEST	4198.	0.00110	0.00110	BASE	14.0	30.0
5895010162209	L 48	NO	AFTER TEST	38700.	0.00420	0.00420	BASE	14.0	30.0
5895010963727	L 49	NO	AFTER TEST	24025.	0.00200	0.00200	BASE	17.0	30.0
5895011126380	L 50	NO	AFTER TEST	19570.	0.01370	0.01370	BASE	16.0	30.0
5895011349225	L 51	NO	AFTER TEST	26780.	0.00800	0.00800	BASE	14.0	30.0

Table B-1. Detailed LRU Information for F-15C PACAF (Continued)

6110005390411	L 52	NO	AFTER TEST	3193.	0.00030	0.00030	BASE	14.0	30.0
6110010498639	L 53	NO	AFTER TEST	4817.	0.00140	0.00140	BASE	14.0	30.0
6605010848224	L 54	NO	AFTER TEST	22145.	0.00530	0.00530	BASE	14.0	30.0
6605010940775	L 55	NO	AFTER TEST	22544.	0.00740	0.00740	BASE	14.0	30.0
6605010954208	L 56	NO	AFTER TEST	139222.	0.02040	0.02040	BASE	14.0	30.0
6610001226625	L 57	NO	AFTER TEST	19972.	0.00440	0.00440	BASE	14.0	30.0
6610001491134	L 58	NO	AFTER TEST	32459.	0.00890	0.00890	BASE	13.0	30.0
6610010903390	L 59	NO	AFTER TEST	22660.	0.00330	0.00330	BASE	10.0	30.0
6610011694770	L 60	NO	AFTER TEST	23936.	0.00400	0.00400	BASE	14.0	30.0
1005001886968	L 61	NO	AFTER TEST	2175.	0.01400	0.01400	BASE	14.0	30.0
1005001886969	L 62	NO	AFTER TEST	2908.	0.00550	0.00550	BASE	14.0	30.0
1005002790528	L 63	NO	AFTER TEST	3529.	0.02120	0.02120	BASE	14.0	30.0
1005010429740	L 64	NO	AFTER TEST	44487.	0.00410	0.00410	BASE	14.0	30.0
1005010932225	L 65	NO	AFTER TEST	5012.	0.00500	0.00500	BASE	14.0	30.0
1005011055476	L 66	NO	AFTER TEST	10475.	0.00220	0.00220	BASE	14.0	30.0
1095001664286	L 67	NO	AFTER TEST	2888.	0.00050	0.00050	BASE	16.0	30.0
1280010315802	L 68	NO	AFTER TEST	638.	0.00030	0.00030	BASE	11.0	30.0
1280010524811	L 69	NO	AFTER TEST	2018.	0.00100	0.00100	BASE	14.0	30.0
1280010542853	L 70	NO	AFTER TEST	481.	0.00040	0.00040	BASE	16.0	30.0
1280010542856	L 71	NO	AFTER TEST	495.	0.00030	0.00030	BASE	15.0	30.0
1280011354647	L 72	NO	AFTER TEST	29648.	0.01060	0.01060	BASE	14.0	30.0
1440010595257BL	L 73	NO	AFTER TEST	37521.	0.00080	0.00080	BASE	14.0	30.0
1440010891384AB	L 74	NO	AFTER TEST	1514.	0.00200	0.00200	BASE	14.0	30.0
1560005186889FX	L 75	NO	AFTER TEST	20148.	0.00060	0.00060	BASE	14.0	30.0
1560005235267FX	L 76	NO	AFTER TEST	24334.	0.00060	0.00060	BASE	14.0	30.0
1560010145787FX	L 77	NO	AFTER TEST	25576.	0.00140	0.00140	BASE	14.0	30.0
1560010564844FX	L 78	NO	AFTER TEST	52188.	0.00050	0.00050	BASE	14.0	30.0
1560010753550FX	L 79	NO	AFTER TEST	2961.	0.00060	0.00060	BASE	13.0	30.0
1560011426673FX	L 80	NO	AFTER TEST	17999.	0.00030	0.00030	BASE	14.0	30.0
1560011825949FX	L 81	NO	AFTER TEST	16424.	0.00050	0.00050	BASE	14.0	30.0
1620002671046	L 82	NO	AFTER TEST	15413.	0.00060	0.00060	BASE	9.0	30.0
1620010362895	L 83	NO	AFTER TEST	3885.	0.00030	0.00030	BASE	14.0	30.0
1620010627002	L 84	NO	AFTER TEST	48153.	0.00060	0.00060	BASE	14.0	30.0
1620011670999	L 85	NO	AFTER TEST	69525.	0.00060	0.00060	BASE	14.0	30.0
1620011671000	L 86	NO	AFTER TEST	69525.	0.00060	0.00060	BASE	14.0	30.0
1630003934771	L 87	NO	AFTER TEST	5944.	0.00060	0.00060	BASE	20.0	30.0
1630010182004	L 88	NO	AFTER TEST	4223.	0.00140	0.00140	BASE	16.0	30.0
1630010585912	L 89	NO	AFTER TEST	6064.	0.01080	0.01080	BASE	14.0	30.0
1630010597069	L 90	NO	AFTER TEST	15238.	0.00250	0.00250	BASE	14.0	30.0
1630010645095	L 91	NO	AFTER TEST	891.	0.00070	0.00070	BASE	17.0	30.0
1630010716112	L 92	NO	AFTER TEST	1810.	0.00890	0.00890	BASE	14.0	30.0
1650002886044	L 93	NO	AFTER TEST	7916.	0.00090	0.00090	BASE	14.0	30.0
1650002952369	L 94	NO	AFTER TEST	8673.	0.00140	0.00140	BASE	14.0	30.0
1650003035851	L 95	NO	AFTER TEST	1782.	0.00030	0.00030	BASE	15.0	30.0
1650003550211	L 96	NO	AFTER TEST	7486.	0.00110	0.00110	BASE	9.0	30.0
1650003550213	L 97	NO	AFTER TEST	19915.	0.00040	0.00040	BASE	15.0	30.0
1650003715854	L 98	NO	AFTER TEST	1545.	0.00060	0.00060	BASE	12.0	30.0
1650004330145	L 99	NO	AFTER TEST	5886.	0.00060	0.00060	BASE	13.0	30.0
1650005168603	L 100	NO	AFTER TEST	2912.	0.00020	0.00020	BASE	12.0	30.0
1650005316029	L 101	NO	AFTER TEST	10974.	0.00170	0.00170	BASE	10.0	30.0
1650005405573	L 102	NO	AFTER TEST	352.	0.00000	0.00000	BASE	23.0	30.0
1650010045794	L 103	NO	AFTER TEST	5013.	0.00030	0.00030	BASE	12.0	30.0
1650010181073	L 104	NO	AFTER TEST	4973.	0.00020	0.00020	BASE	21.0	30.0
1650010189089	L 105	NO	AFTER TEST	13907.	0.00160	0.00160	BASE	14.0	30.0
1650010206212	L 106	NO	AFTER TEST	9600.	0.00090	0.00090	BASE	9.0	30.0
1650010208093	L 107	NO	AFTER TEST	5156.	0.00050	0.00050	BASE	9.0	30.0
1650010297620	L 108	NO	AFTER TEST	3477.	0.00030	0.00030	BASE	13.0	30.0

Table B-1. Detailed LRU Information for F-15C PACAF (Continued)

1650010350799	L 109	NO	AFTER TEST	4024.	0.00090	0.00090	BASE	15.0	30.0
1650010505228	L 110	NO	AFTER TEST	5248.	0.00090	0.00090	BASE	12.0	30.0
1650010520916	L 111	NO	AFTER TEST	12921.	0.00070	0.00070	BASE	16.0	30.0
1650010657768	L 112	NO	AFTER TEST	24875.	0.00210	0.00210	BASE	13.0	30.0
1650010912313	L 113	NO	AFTER TEST	11372.	0.00080	0.00080	BASE	14.0	30.0
1650010964603	L 114	NO	AFTER TEST	38831.	0.00190	0.00190	BASE	14.0	30.0
1650011055523	L 115	NO	AFTER TEST	39564.	0.00220	0.00220	BASE	14.0	30.0
1650011215786	L 116	NO	AFTER TEST	10193.	0.00060	0.00060	BASE	8.0	30.0
1650011216981	L 117	NO	AFTER TEST	7246.	0.00060	0.00060	BASE	14.0	30.0
1650011226948	L 118	NO	AFTER TEST	14706.	0.00040	0.00040	BASE	13.0	30.0
1650011537932	L 119	NO	AFTER TEST	5026.	0.00040	0.00040	BASE	14.0	30.0
1650011739697	L 120	NO	AFTER TEST	158593.	0.00140	0.00140	BASE	14.0	30.0
1660001239568	L 121	NO	AFTER TEST	946.	0.00010	0.00010	BASE	21.0	30.0
1660001239583	L 122	NO	AFTER TEST	893.	0.00010	0.00010	BASE	13.0	30.0
1660001239587	L 123	NO	AFTER TEST	1752.	0.00060	0.00060	BASE	14.0	30.0
1660002381362BO	L 124	NO	AFTER TEST	2265.	0.00090	0.00090	BASE	12.0	30.0
1660002738669	L 125	NO	AFTER TEST	14214.	0.00240	0.00240	BASE	14.0	30.0
1660002876868	L 126	NO	AFTER TEST	1501.	0.00170	0.00170	BASE	11.0	30.0
1660002885532	L 127	NO	AFTER TEST	1074.	0.00010	0.00010	BASE	13.0	30.0
1660002929104	L 128	NO	AFTER TEST	2511.	0.00050	0.00050	BASE	12.0	30.0
1660003277052	L 129	NO	AFTER TEST	5651.	0.00140	0.00140	BASE	14.0	30.0
1660003679453	L 130	NO	AFTER TEST	839.	0.00020	0.00020	BASE	13.0	30.0
1660005678852BO	L 131	NO	AFTER TEST	1952.	0.00480	0.00480	BASE	13.0	30.0
1660007980235	L 132	NO	AFTER TEST	634.	0.00010	0.00010	BASE	19.0	30.0
1660010040798	L 133	NO	AFTER TEST	6529.	0.00050	0.00050	BASE	11.0	30.0
1660010155017	L 134	NO	AFTER TEST	2965.	0.00230	0.00230	BASE	14.0	30.0
1660010214822	L 135	NO	AFTER TEST	4668.	0.00170	0.00170	BASE	14.0	30.0
1660010215625	L 136	NO	AFTER TEST	2118.	0.00200	0.00200	BASE	12.0	30.0
1660010359636TP	L 137	NO	AFTER TEST	17747.	0.00240	0.00240	BASE	14.0	30.0
1660010619097	L 138	NO	AFTER TEST	1105.	0.00050	0.00050	BASE	14.0	30.0
1660010631213	L 139	NO	AFTER TEST	24703.	0.00070	0.00070	BASE	14.0	30.0
1660010808229	L 140	NO	AFTER TEST	10375.	0.00280	0.00280	BASE	14.0	30.0
1660011374105	L 141	NO	AFTER TEST	15285.	0.00110	0.00110	BASE	14.0	30.0
1680001238168	L 142	NO	AFTER TEST	4893.	0.00050	0.00050	BASE	14.0	30.0
1680001323272	L 143	NO	AFTER TEST	9570.	0.00020	0.00020	BASE	14.0	30.0
1680002988837	L 144	NO	AFTER TEST	7234.	0.00020	0.00020	BASE	14.0	30.0
1680003141930	L 145	NO	AFTER TEST	1259.	0.00140	0.00140	BASE	14.0	30.0
1680010041244FX	L 146	NO	AFTER TEST	17659.	0.00080	0.00080	BASE	14.0	30.0
1680010485183	L 147	NO	AFTER TEST	3438.	0.00080	0.00080	BASE	14.0	30.0
1680010524890	L 148	NO	AFTER TEST	4635.	0.00010	0.00010	BASE	10.0	30.0
1680010530071LS	L 149	NO	AFTER TEST	4120.	0.00020	0.00020	BASE	11.0	30.0
1680010652355	L 150	NO	AFTER TEST	3151.	0.00030	0.00030	BASE	18.0	30.0
1680010946707	L 151	NO	AFTER TEST	3716.	0.00020	0.00020	BASE	14.0	30.0
1680011390166	L 152	NO	AFTER TEST	3614.	0.00110	0.00110	BASE	14.0	30.0
1680011625850FX	L 153	NO	AFTER TEST	21309.	0.00080	0.00080	BASE	14.0	30.0
2620010632361	L 154	NO	AFTER TEST	139.	0.02170	0.02170	BASE	32.0	30.0
2620011486221	L 155	NO	AFTER TEST	274.	0.05060	0.05060	BASE	59.0	30.0
28350039018[illegible]4	L 156	NO	AFTER TEST	3472.	0.00260	0.00260	BASE	14.0	30.0
2835010207249	L 157	NO	AFTER TEST	38574.	0.00180	0.00180	BASE	14.0	30.0
2835010346948	L 158	NO	AFTER TEST	171108.	0.00360	0.00360	BASE	14.0	30.0
2835010881009	L 159	NO	AFTER TEST	33321.	0.00100	0.00100	BASE	11.0	30.0
2835010912433	L 160	NO	AFTER TEST	102205.	0.00290	0.00290	BASE	14.0	30.0
2840003275432PT	L 161	NO	AFTER TEST	6387.	0.00020	0.00020	BASE	13.0	30.0
2840005232036PT	L 162	NO	AFTER TEST	119.	0.00200	0.00200	BASE	14.0	30.0
2840005341824PT	L 163	NO	AFTER TEST	474.	0.00020	0.00020	BASE	14.0	30.0
2840010491150PT	L 164	NO	AFTER TEST	19761.	0.00240	0.00240	BASE	14.0	30.0
2840011028596PT	L 165	NO	AFTER TEST	4882.	0.00050	0.00050	BASE	14.0	30.0

Table B-1. Detailed LRU Information for F-15C PACAF (Continued)

2840011288348PT	L 166	NO	AFTER TEST	604.	0.00170	0.00170	BASE	8.0	30.0
2840011288349PT	L 167	NO	AFTER TEST	349.	0.00100	0.00100	BASE	14.0	30.0
2840011288437PT	L 168	NO	AFTER TEST	6191.	0.00220	0.00220	BASE	20.0	30.0
2840011291044PT	L 169	NO	AFTER TEST	437.	0.00160	0.00160	BASE	12.0	30.0
2840011433254PT	L 170	NO	AFTER TEST	443.	0.00100	0.00100	BASE	15.0	30.0
2840011471898PT	L 171	NO	AFTER TEST	3976.	0.00020	0.00020	BASE	10.0	30.0
2840011471899PT	L 172	NO	AFTER TEST	4090.	0.00050	0.00050	BASE	15.0	30.0
2840011559148PT	L 173	NO	AFTER TEST	1571.	0.00070	0.00070	BASE	14.0	30.0
2840011649087PT	L 174	NO	AFTER TEST	2577.	0.00010	0.00010	BASE	14.0	30.0
2840011802935PT	L 175	NO	AFTER TEST	350.	0.00040	0.00040	BASE	29.0	30.0
2840011802941PT	L 176	NO	AFTER TEST	547.	0.00040	0.00040	BASE	14.0	30.0
2915003353183	L 177	NO	AFTER TEST	1092.	0.00030	0.00030	BASE	14.0	30.0
2915005370336	L 178	NO	AFTER TEST	4634.	0.00010	0.00010	BASE	20.0	30.0
2915010097932	L 179	NO	AFTER TEST	562.	0.00110	0.00110	BASE	14.0	30.0
2915010350276PT	L 180	NO	AFTER TEST	17187.	0.00190	0.00190	BASE	14.0	30.0
2915010353771PT	L 181	NO	AFTER TEST	1830.	0.00020	0.00020	BASE	10.0	30.0
2915010562716	L 182	NO	AFTER TEST	4841.	0.00040	0.00040	BASE	14.0	30.0
2915010653149	L 183	NO	AFTER TEST	1002.	0.00140	0.00140	BASE	14.0	30.0
2915010658525	L 184	NO	AFTER TEST	5223.	0.00070	0.00070	BASE	10.0	30.0
2915010659589PT	L 185	NO	AFTER TEST	25853.	0.00150	0.00150	BASE	14.0	30.0
2915010718325PT	L 186	NO	AFTER TEST	5071.	0.00020	0.00020	BASE	14.0	30.0
2915010753518PT	L 187	NO	AFTER TEST	35123.	0.00210	0.00210	BASE	13.0	30.0
2915010819055PT	L 188	NO	AFTER TEST	5371.	0.00080	0.00080	BASE	14.0	30.0
2915010970518	L 189	NO	AFTER TEST	1347.	0.00080	0.00080	BASE	31.0	30.0
2915011076177PT	L 190	NO	AFTER TEST	11064.	0.00060	0.00060	BASE	14.0	30.0
2915011160968	L 191	NO	AFTER TEST	1192.	0.00170	0.00170	BASE	14.0	30.0
2915011376551PT	L 192	NO	AFTER TEST	7195.	0.00100	0.00100	BASE	14.0	30.0
2915011620998PT	L 193	NO	AFTER TEST	35799.	0.00350	0.00350	BASE	14.0	30.0
2915011699461	L 194	NO	AFTER TEST	435.	0.00020	0.00020	BASE	14.0	30.0
2915011783445	L 195	NO	AFTER TEST	5987.	0.00090	0.00090	BASE	14.0	30.0
2915012037229PT	L 196	NO	AFTER TEST	188734.	0.00200	0.00200	BASE	14.0	30.0
2925003276212PT	L 197	NO	AFTER TEST	1110.	0.00020	0.00020	BASE	14.0	30.0
2925003276214PT	L 198	NO	AFTER TEST	1832.	0.00020	0.00020	BASE	14.0	30.0
2925003276216PT	L 199	NO	AFTER TEST	3769.	0.00040	0.00040	BASE	14.0	30.0
2925010228332PT	L 200	NO	AFTER TEST	3143.	0.00080	0.00080	BASE	11.0	30.0
2925010685284PT	L 201	NO	AFTER TEST	875.	0.00010	0.00010	BASE	24.0	30.0
2925010753343PT	L 202	NO	AFTER TEST	1963.	0.00120	0.00120	BASE	12.0	30.0
2925011602149PT	L 203	NO	AFTER TEST	8909.	0.00090	0.00090	BASE	14.0	30.0
2935010078381PT	L 204	NO	AFTER TEST	891.	0.00060	0.00060	BASE	14.0	30.0
2945011441402PT	L 205	NO	AFTER TEST	1739.	0.00010	0.00010	BASE	14.0	30.0
2995005343027PT	L 206	NO	AFTER TEST	1221.	0.00030	0.00030	BASE	25.0	30.0
2995010995028PT	L 207	NO	AFTER TEST	7727.	0.00030	0.00030	BASE	16.0	30.0
2995011498836PT	L 208	NO	AFTER TEST	1475.	0.00110	0.00110	BASE	14.0	30.0
2995011595332	L 209	NO	AFTER TEST	464.	0.00090	0.00090	BASE	14.0	30.0
2995011596742	L 210	NO	AFTER TEST	1333.	0.00320	0.00320	BASE	14.0	30.0
3110011288083PT	L 211	NO	AFTER TEST	168.	0.00190	0.00190	BASE	14.0	30.0
4320011878144PT	L 212	NO	AFTER TEST	10076.	0.00010	0.00010	BASE	14.0	30.0
4710011756154PT	L 213	NO	AFTER TEST	547.	0.00040	0.00040	BASE	14.0	30.0
4710011795109PT	L 214	NO	AFTER TEST	422.	0.00020	0.00020	BASE	12.0	30.0
4810010070536	L 215	NO	AFTER TEST	3119.	0.00150	0.00150	BASE	14.0	30.0
4810010352340PT	L 216	NO	AFTER TEST	3167.	0.00010	0.00010	BASE	14.0	30.0
4810010898900	L 217	NO	AFTER TEST	1671.	0.00020	0.00020	BASE	14.0	30.0
4810010911930	L 218	NO	AFTER TEST	1714.	0.00040	0.00040	BASE	14.0	30.0
4810010944567	L 219	NO	AFTER TEST	2107.	0.00010	0.00010	BASE	14.0	30.0
4810010944568	L 220	NO	AFTER TEST	2371.	0.00020	0.00020	BASE	14.0	30.0
4820003050289TP	L 221	NO	AFTER TEST	2844.	0.00260	0.00260	BASE	13.0	30.0
4820003133307	L 222	NO	AFTER TEST	3557.	0.00020	0.00020	BASE	14.0	30.0

Table B-1. Detailed LRU Information for F-15C PACAF (Continued)

4820003373985	L 223	NO	AFTER TEST	505.	0.00000	0.00000	BASE	20.0	30.0
4820010681105	L 224	NO	AFTER TEST	9574.	0.00030	0.00030	BASE	24.0	30.0
4820010955359PT	L 225	NO	AFTER TEST	7054.	0.00090	0.00090	BASE	14.0	30.0
4820011526285PT	L 226	NO	AFTER TEST	920.	0.00020	0.00020	BASE	14.0	30.0
5821010934574	L 227	NO	AFTER TEST	7482.	0.00090	0.00090	BASE	14.0	30.0
5821010934632	L 228	NO	AFTER TEST	2602.	0.00090	0.00090	BASE	14.0	30.0
5821010934635	L 229	NO	AFTER TEST	14304.	0.00410	0.00410	BASE	14.0	30.0
5821010934663	L 230	NO	AFTER TEST	1055.	0.00090	0.00090	BASE	16.0	30.0
5821010934664	L 231	NO	AFTER TEST	1248.	0.00060	0.00060	BASE	14.0	30.0
5821010939985	L 232	NO	AFTER TEST	881.	0.00030	0.00030	BASE	14.0	30.0
5821011178463	L 233	NO	AFTER TEST	2152.	0.00240	0.00240	BASE	29.0	30.0
5821011280394	L 234	NO	AFTER TEST	10500.	0.00300	0.00300	BASE	14.0	30.0
5821011498710	L 235	NO	AFTER TEST	748.	0.00030	0.00030	BASE	16.0	30.0
5821011498809	L 236	NO	AFTER TEST	1959.	0.00190	0.00190	BASE	16.0	30.0
5826010603893	L 237	NO	AFTER TEST	6265.	0.00080	0.00080	BASE	[illegible].0	30.0
5841010451066	L 238	NO	AFTER TEST	3817.	0.00030	0.00030	BASE	33.0	30.0
5841010510385	L 239	NO	AFTER TEST	6445.	0.00020	0.00020	BASE	14.0	30.0
5841010588861	L 240	NO	AFTER TEST	3529.	0.00010	0.00010	BASE	13.0	30.0
5841010630856	L 241	NO	AFTER TEST	108154.	0.00080	0.00080	BASE	11.0	30.0
5841010714135	L 242	NO	AFTER TEST	4600.	0.00020	0.00020	BASE	14.0	30.0
5841010808787	L 243	NO	AFTER TEST	20920.	0.00060	0.00060	BASE	16.0	30.0
5841011712635	L 244	NO	AFTER TEST	3728.	0.00070	0.00070	BASE	14.0	30.0
5841011713031	L 245	NO	AFTER TEST	3213.	0.00130	0.00130	BASE	14.0	30.0
5865000037461EW	L 246	NO	AFTER TEST	817.	0.00100	0.00100	BASE	12.0	30.0
5865000037464EW	L 247	NO	AFTER TEST	5800.	0.00390	0.00390	BASE	10.0	30.0
5865000076945EW	L 248	NO	AFTER TEST	3208.	0.00980	0.00980	BASE	23.0	30.0
5865000076949EW	L 249	NO	AFTER TEST	4627.	0.01170	0.01170	BASE	16.0	30.0
5865000076950EW	L 250	NO	AFTER TEST	1530.	0.00290	0.00290	BASE	20.0	30.0
5865000094381EW	L 251	NO	AFTER TEST	9730.	0.00290	0.00290	BASE	12.0	30.0
5865000[illegible]33361EW	L 252	NO	AFTER TEST	822.	0.00290	0.00290	BASE	11.0	30.0
5865001559243EW	L 253	NO	AFTER TEST	559.	0.00130	0.00130	BASE	9.0	30.0
5865001559266EW	L 254	NO	AFTER TEST	8980.	0.00780	0.00780	BASE	9.0	30.0
5865001559489EW	L 255	NO	AFTER TEST	1830.	0.00630	0.00630	BASE	16.0	30.0
5865001559499EW	L 256	NO	AFTER TEST	890.	0.00290	0.00290	BASE	12.0	30.0
5865001627964EW	L 257	NO	AFTER TEST	4217.	0.00690	0.00690	BASE	13.0	30.0
5865001854444EW	L 258	NO	AFTER TEST	4177.	0.01270	0.01270	BASE	19.0	30.0
5865001955987EW	L 259	NO	AFTER TEST	1368.	0.00390	0.00390	BASE	16.0	30.0
5865001994210EW	L 260	NO	AFTER TEST	12929.	0.01370	0.01370	BASE	16.0	30.0
5865003073292EW	L 261	NO	AFTER TEST	433.	0.02050	0.02050	BASE	17.0	30.0
5865003151482EW	L 262	NO	AFTER TEST	2680.	0.00200	0.00200	BASE	11.0	30.0
5865003151491EW	L 263	NO	AFTER TEST	825.	0.02050	0.02050	BASE	13.0	30.0
5865003151499EW	L 264	NO	AFTER TEST	1973.	0.00780	0.00780	BASE	16.0	30.0
5865003217636EW	L 265	NO	AFTER TEST	1569.	0.00490	0.00490	BASE	11.0	30.0
5865003217650EW	L 266	NO	AFTER TEST	362.	0.00030	0.00030	BASE	11.0	30.0
5865003655459EW	L 267	NO	AFTER TEST	1843.	0.01760	0.01760	BASE	12.0	30.0
5865003713344EW	L 268	NO	AFTER TEST	7904.	0.01760	0.01760	BASE	18.0	30.0
5865004438630EW	L 269	NO	AFTER TEST	610.	0.00030	0.00030	BASE	22.0	30.0
5865004520326EW	L 270	NO	AFTER TEST	271.	0.00350	0.00350	BASE	14.0	30.0
5865004520327EW	L 271	NO	AFTER TEST	185.	0.00200	0.00200	BASE	12.0	30.0
5865004520328EW	L 272	NO	AFTER TEST	611.	0.00140	0.00140	BASE	11.0	30.0
5865004671140EW	L 273	NO	AFTER TEST	3631.	0.00790	0.00790	BASE	14.0	30.0
5865004671191EW	L 274	NO	AFTER TEST	4177.	0.00330	0.00330	BASE	14.0	30.0
5865004723317EW	L 275	NO	AFTER TEST	822.	0.00100	0.00100	BASE	14.0	30.0
5865004764442EW	L 276	NO	AFTER TEST	6273.	0.01470	0.01470	BASE	16.0	30.0
5865004764443EW	L 277	NO	AFTER TEST	3703.	0.02440	0.02440	BASE	16.0	30.0
5865004775921EW	L 278	NO	AFTER TEST	2818.	0.00100	0.00100	BASE	12.0	30.0
5865004775923EW	L 279	NO	AFTER TEST	2366.	0.00000	0.00000	BASE	14.0	30.0

Table B-1. Detailed LRU Information for F-15C PACAF (Continued)

5865005562035EW	L 280	NO	AFTER TEST	331.	0.00200	0.00200	BASE	18.0	30.0
5865005562036EW	L 281	NO	AFTER TEST	531.	0.00390	0.00390	BASE	14.0	30.0
5865005562037EW	L 282	NO	AFTER TEST	161.	0.00180	0.00180	BASE	11.0	30.0
5865005562038EW	L 283	NO	AFTER TEST	1270.	0.00200	0.00200	BASE	15.0	30.0
5865005562039EW	L 284	NO	AFTER TEST	1245.	0.01170	0.01170	BASE	16.0	30.0
5865005562041EW	L 285	NO	AFTER TEST	224.	0.00100	0.00100	BASE	22.0	30.0
5865005562055EW	L 286	NO	AFTER TEST	376.	0.00390	0.00390	BASE	15.0	30.0
5865005562062EW	L 287	NO	AFTER TEST	1352.	0.00100	0.00100	BASE	17.0	30.0
5865005562103EW	L 288	NO	AFTER TEST	951.	0.00290	0.00290	BASE	8.0	30.0
5865005562104EW	L 289	NO	AFTER TEST	751.	0.00720	0.00720	BASE	16.0	30.0
5865005562114EW	L 290	NO	AFTER TEST	1293.	0.00610	0.00610	BASE	15.0	30.0
5865005562122EW	L 291	NO	AFTER TEST	203.	0.00420	0.00420	BASE	17.0	30.0
5865006035397EW	L 292	NO	AFTER TEST	560.	0.00070	0.00070	BASE	25.0	30.0
5865006035404EW	L 293	NO	AFTER TEST	980.	0.00170	0.00170	BASE	16.0	30.0
5865006035409EW	L 294	NO	AFTER TEST	3999.	0.00120	0.00120	BASE	16.0	30.0
5865006035457EW	L 295	NO	AFTER TEST	71.	0.00070	0.00070	BASE	13.0	30.0
5865006035458EW	L 296	NO	AFTER TEST	692.	0.00030	0.00030	BASE	18 0	30.0
5865006035460EW	L 297	NO	AFTER TEST	722.	0.00020	0.00020	BASE	32.0	30.0
5865006035461EW	L 298	NO	AFTER TEST	664.	0.00070	0.00070	BASE	19.0	30.0
5865006035462EW	L 299	NO	AFTER TEST	5031.	0.00120	0.00120	BASE	14.0	30.0
5865006035520EW	L 300	NO	AFTER TEST	714.	0.00040	0.00040	BASE	26.0	30.0
5865006035524EW	L 301	NO	AFTER TEST	3592.	0.00130	0.00130	BASE	14.0	30.0
5865007598099EW	L 302	NO	AFTER TEST	10973.	0.00240	0.00240	BASE	10.0	30.0
5865010134840EW	L 303	NO	AFTER TEST	1338.	0.00290	0.00290	BASE	16.0	30.0
5865010135205EW	L 304	NO	AFTER TEST	292.	0.00200	0.00200	BASE	10.0	30.0
5865010135206EW	L 305	NO	AFTER TEST	560.	0.00200	0.00200	BASE	15.0	30.0
5865010142724EW	L 306	NO	AFTER TEST	2554.	0.00010	0.00010	BASE	15.0	30.0
5865010346003EW	L 307	NO	AFTER TEST	1423.	0.00050	0.00050	BASE	15.0	30.0
5865010599021EW	L 308	NO	AFTER TEST	1315.	0.00030	0.00030	BASE	24.0	30.0
5865010650216EW	L 309	NO	AFTER TEST	1789.	0.00050	0.00050	BASE	8.0	30.0
5865010666206EW	L 310	NO	AFTER TEST	1396.	0.00080	0.00080	BASE	21.0	30.0
5865010668149EW	L 311	NO	AFTER TEST	1326.	0.00070	0.00070	BASE	30.0	30.0
5865010770497EW	L 312	NO	AFTER TEST	6013.	0.01560	0.01560	BASE	16.0	30.0
5865010844520EW	L 313	NO	AFTER TEST	2138.	0.00100	0.00100	BASE	22.0	30.0
5865010861000EW	L 314	NO	AFTER TEST	2138.	0.00300	0.00300	BASE	11.0	30.0
5865010861001EW	L 315	NO	AFTER TEST	3097.	0.00420	0.00420	BASE	14.0	30.0
5865010861002EW	L 316	NO	AFTER TEST	2138.	0.00070	0.00070	BASE	22.0	30.0
5865010879065EW	L 317	NO	AFTER TEST	675.	0.00020	0.00020	BASE	14.0	30.0
5865010880956EW	L 318	NO	AFTER TEST	2141.	0.00030	0.00030	BASE	13.0	30.0
5865010881019EW	L 319	NO	AFTER TEST	2647.	0.00170	0.00170	BASE	17.0	30.0
5865010881025EW	L 320	NO	AFTER TEST	12248.	0.00130	0.00130	BASE	14.0	30.0
5865010889067EW	L 321	NO	AFTER TEST	716.	0.00010	0.00010	BASE	15.0	30.0
5865010972494EW	L 322	NO	AFTER TEST	602.	0.00010	0.00010	BASE	14.0	30.0
5865010998141EW	L 323	NO	AFTER TEST	650.	0.00060	0.00060	BASE	14.0	30.0
5865010999833EW	L 324	NO	AFTER TEST	689.	0.00030	0.00030	BASE	33.0	30.0
5865011172948EW	L 325	NO	AFTER TEST	497.	0.00010	0.00010	BASE	14.0	30.0
5865011185359EW	L 326	NO	AFTER TEST	3042.	0.00030	0.00030	BASE	23.0	30.0
5865011339957EW	L 327	NO	AFTER TEST	1938.	0.00190	0.00190	BASE	14.0	30.0
5865011341091EW	L 328	NO	AFTER TEST	3152.	0.00100	0.00100	BASE	14.0	30.0
5865011549042EW	L 329	NO	AFTER TEST	2580.	0.00040	0.00040	BASE	16.0	30.0
5865011701119EW	L 330	NO	AFTER TEST	1588.	0.00010	0.00010	BASE	14.0	30.0
5865012112336EW	L 331	NO	AFTER TEST	3200.	0.00090	0.00090	BASE	14.0	30.0
5865012119086EW	L 332	NO	AFTER TEST	2000.	0.00170	0.00170	BASE	14.0	30.0
5895001151029	L 333	NO	AFTER TEST	1309.	0.00260	0.00260	BASE	16.0	30.0
5895010444987	L 334	NO	AFTER TEST	1303.	0.00070	0.00070	BASE	14.0	30.0
5895010959593	L 335	NO	AFTER TEST	4093.	0.00320	0.00320	BASE	14.0	30.0
5895011132491	L 336	NO	AFTER TEST	2630.	0.00010	0.00010	BASE	14.0	30.0

Table B-1. Detailed LRU Information for F-15C PACAF (Continued)

5895011184625	L 337	NO	AFTER TEST	263.	0.00090	0.00090	BASE	10.0	30.0
5945003696992	L 338	NO	AFTER TEST	1725.	0.00020	0.00020	BASE	20.0	30.0
5985010304158EW	L 339	NO	AFTER TEST	2876.	0.00050	0.00050	BASE	14.0	30.0
5985010304159EW	L 340	NO	AFTER TEST	2549.	0.00400	0.00400	BASE	14.0	30.0
5995003904515CW	L 341	NO	AFTER TEST	6397.	0.00090	0.00090	BASE	15.0	30.0
5995011310957EW	L 342	NO	AFTER TEST	4874.	0.00100	0.00100	BASE	14.0	30.0
6115004690710	L 343	NO	AFTER TEST	10374.	0.00190	0.00190	BASE	14.0	30.0
6115011213632UH	L 344	NO	AFTER TEST	19692.	0.00120	0.00120	BASE	14.0	30.0
6340003327300	L 345	NO	AFTER TEST	2972.	0.00020	0.00020	BASE	14.0	30.0
6340010772900NT	L 346	NO	AFTER TEST	3791.	0.00040	0.00040	BASE	11.0	30.0
6605003142536	L 347	NO	AFTER TEST	2013.	0.00140	0.00140	BASE	14.0	30.0
6605010423335	L 348	NO	AFTER TEST	8902.	0.00160	0.00160	BASE	14.0	30.0
6605010445026	L 349	NO	AFTER TEST	3405.	0.00050	0.00050	BASE	15.0	30.0
6605010470163	L 350	NO	AFTER TEST	1386.	0.00020	0.00020	BASE	15.0	30.0
6605010977155	L 351	NO	AFTER TEST	1276.	0.00070	0.00070	BASE	14.0	30.0
6610000000122	L 352	NO	AFTER TEST	14082.	0.00150	0.00150	BASE	12.0	30.0
6610001342251	L 353	NO	AFTER TEST	3708.	0.00030	0.00030	BASE	10.0	30.0
6610001342259	L 354	NO	AFTER TEST	1643.	0.00140	0.00140	BASE	13.0	30.0
6610001342260	L 355	NO	AFTER TEST	4307.	0.00140	0.00140	BASE	11.0	30.0
6610001600905	L 356	NO	AFTER TEST	3745.	0.00170	0.00170	BASE	17.0	30.0
6610002963574	L 357	NO	AFTER TEST	939.	0.00050	0.00050	BASE	10.0	30.0
6610003036706	L 358	NO	AFTER TEST	2411.	0.00040	0.00040	BASE	12.0	30.0
6610003293495	L 359	NO	AFTER TEST	1214.	0.00150	0.00150	BASE	12.0	30.0
6610003616686	L 360	NO	AFTER TEST	564.	0.00070	0.00070	BASE	10.0	30.0
6610005357722	L 361	NO	AFTER TEST	2199.	0.00380	0.00380	BASE	15.0	30.0
6610010379144	L 362	NO	AFTER TEST	19047.	0.00480	0.00480	BASE	14.0	30.0
6610010424831	L 363	NO	AFTER TEST	17922.	0.00600	0.00600	BASE	14.0	30.0
6610010933356	L 364	NO	AFTER TEST	3624.	0.00070	0.00070	BASE	16.0	30.0
6610011676617	L 365	NO	AFTER TEST	11588.	0.00570	0.00570	BASE	20.0	30.0
6610011687039	L 366	NO	AFTER TEST	928.	0.00030	0.00030	BASE	14.0	30.0
6610011687042	L 367	NO	AFTER TEST	927.	0.00010	0.00010	BASE	14.0	30.0
6610011692283	L 368	NO	AFTER TEST	670.	0.00010	0.00010	BASE	14.0	30.0
6615001377514	L 369	NO	AFTER TEST	29601.	0.00170	0.00170	BASE	13.0	30.0
6615002624314	L 370	NO	AFTER TEST	13993.	0.00030	0.00030	BASE	13.0	30.0
6615003036728	L 371	NO	AFTER TEST	30605.	0.00830	0.00830	BASE	12.0	30.0
6615003036730	L 372	NO	AFTER TEST	1867.	0.00120	0.00120	BASE	16.0	30.0
6615010154794	L 373	NO	AFTER TEST	27553.	0.00280	0.00280	BASE	20.0	30.0
6615010214234	L 374	NO	AFTER TEST	5452.	0.00060	0.00060	BASE	14.0	30.0
6615010950962	L 375	NO	AFTER TEST	26189.	0.00300	0.00300	BASE	14.0	30.0
6615011497475	L 376	NO	AFTER TEST	13596.	0.00110	0.00110	BASE	14.0	30.0
6620001487306	L 377	NO	AFTER TEST	2259.	0.00110	0.00110	BASE	14.0	30.0
6620004689824	L 378	NO	AFTER TEST	3871.	0.00110	0.00110	BASE	9.0	30.0
6620010872354	L 379	NO	AFTER TEST	3361.	0.00220	0.00220	BASE	12.0	30.0
6645000763050	L 380	NO	AFTER TEST	546.	0.00180	0.00180	BASE	12.0	30.0
6680010684284	L 381	NO	AFTER TEST	662.	0.00200	0.00200	BASE	10.0	30.0
6680011033419	L 382	NO	AFTER TEST	6351.	0.00180	0.00180	BASE	19.0	30.0
6680011066215	L 383	NO	AFTER TEST	6984.	0.00150	0.00150	BASE	17.0	30.0
6680011288000PT	L 384	NO	AFTER TEST	10712.	0.00730	0.00730	BASE	14.0	30.0
6685003336763	L 385	NO	AFTER TEST	415.	0.00050	0.00050	BASE	16.0	30.0
6685010482889NT	L 386	NO	AFTER TEST	2984.	0.00140	0.00140	BASE	14.0	30.0
7021004775716	L 387	NO	AFTER TEST	49372.	0.00070	0.00070	BASE	14.0	30.0

ABBREVIATIONS

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ACIM	Availability Centered Inventory Model
AFLC	Air Force Logistics Command
AIS	avionics intermediate shop
ASD(P&L)	Assistant Secretary of Defense (Production and Logistics)
ATF	advanced tactical fighter
BLSS	Base Level Self-Sufficiency Spares
CASEE	Comprehensive Aircraft Support Effectiveness Evaluation
CER	cost-estimating relationship
CIRF	Centralized Intermediate Repair Facility
DoD	Department of Defense
DSPO	Defense Systems Program Office
Dyna-METRIC	Dynamic Multi-Echelon Technique for Recoverable Item Control
EOQ	economic order quantities
FMC	fully mission capable
FSD	full scale development
IDA	Institute for Defense Analyses
IOC	inital operational capability
LCOM	Logistic Composite Model
LH	Light Helicopter
LRM	line-replaceable module
LRU	line-replaceable unit
MIME	Multi-Item, Multi-Echelon
MQPA	minimum quantity per aircraft
MTBCF	mean time between critical failure
MTBF	mean time between failure
MTTR	mean time to repair
NFMC	not fully mission capable
NMCS	not mission capable status
NOP	non-optimized
NRTS	not repairable this site
O&S	operating and support

OSD	Office of the Secretary of Defense
PC	personal computer
PMC	partially mission capable
QPA	quantity per aircraft
RR	Remove and Replace
RRR	Remove, Repair, and Replace
SESAME	Selective Stockage for Availability, Multi-Echelon
SPECTRUM	Simulation Package for the Evaluation by Computer Techniques of Readiness, Utilization, and Maintenance
SRU	shop-replaceable unit
TAT	turnaround time
VHSIC	very high-speed integrated circuits
WRSK	war reserve spares kit
WSMIS	Weapon System Management Information System